RAIN

PROJECT

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RAIN – Risk Analysis of Infrastructure Networks in Response to Extreme Weather

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Analysis of Practical Remediation Strategies for discrete Infrastructure systems

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1 Executive Summary

The RAIN project aims to provide an operational analysis framework which minimises the impact of extreme weather events on critical components of EU infrastructure. Work Package 7 of the project considers mitigation strategies with a focus on measures that can be adopted to improve the resilience of the existing infrastructure network. These measures include physical adaptations and changes to management strategies. This deliverable focuses on the identification of engineering solutions which increase the level of redundancy and prevent cascading effects. Solutions for extreme weather events identified in Work Package 2 of the project are considered.

In the introductory chapter, the increasing natural weather hazards in Europe are presented through several recent events, such as the major floods experienced in the Danube catchment during 2013 and 2014 and freezing rain experienced in Slovenia in 2014. A general overview of how climate change impacts on infrastructure is also presented.

The report is divided into seven sections, each describing the specific impacts of severe weather hazards on different critical infrastructure which include; Tunnels and Bridges for road and rail networks, Road Pavements, Rail Tracks (including Switches and Crossings), Energy lines (cables, pylons & OH lines) and Dams which form parts of the Energy Infrastructure network and Slopes (both natural and manmade structures) which can be part of the transport (e.g. embankments) and energy (e.g. dams) networks.

For each of the critical infrastructure assets appropriate remediation/mitigation strategies are identified and discussed. The methods considered will increase the safety and reliability of the network. Decisions by infrastructure managers on how to invest limited funding will depend on a many factors including; the available budget, political focus, technical, societal and environmental factors. The influence of many of these factors will be considered in the upcoming Deliverable 7.2 of Work Package 7, through the use of a technical impact matrix method. This will allow the proposed remediation strategies and solutions already identified in this deliverable to be ranked. It will be accompanied with an Operational Report assessing both the advantages and disadvantages of the various maintenance strategies.

2 Introduction

2.1 Background

2.1.1 Engineering Solutions to Increase Resilience to Climate Effects

The elements of infrastructure considered in this report include; bridges, pavements, slopes, rail tracks including switches and crossings, tunnels, energy lines, pylons and dams. Failure of these elements of infrastructure is rising due to the occurrence of more frequent and extreme weather events, largely due to the effects of climate change. The hazards considered in this report are in keeping with those identified in WP2 of the RAIN project, e.g. heavy rainfall, windstorms, coastal floods, river floods, lightning, tornadoes, hail, snow, ice, forest fires and freezing rain. Certain elements of infrastructure are particularly susceptible to failure due to particular hazards, e.g. heavy rainfall can cause slope instability, river floods can result in bridge scour and windstorms can affect overhead cables. In this report each element of infrastructure is first defined, examples of typical failures are presented and the impacts described. The core of the report is a presentation of remediation and preventive measures which can be applied to increase the resilience of the element of infrastructure to the climate hazards most likely to cause failure.

Extreme Weather Events

Transport systems could potentially be affected by a multitude of changes in the future climate, such as, for example, hotter summer conditions, extreme precipitation events, higher wind and sea level rise. These effects could include, traffic disruption, accelerated deterioration processes, increased risk of sudden collapse and, in the most severe cases, fatalities. Weather-induced traffic disruptions can also result in important consequences to the economy as a result in disruption of supply chains and very high replacements costs for existing infrastructure.

The relationship between climate and infrastructure performance is complex and it is difficult to predict the effect on the internal performance of a structure as a result of changes in the external environment. A comparison of the Nordic countries, performed by The Swedish National Road and the Transport Research Institute (VTI 2013), shows that the impacts depend not only on climate change, but also on the topography, the geographic location of inhabited areas and the location of the infrastructure. For road transport infrastructures, the impact of weather events represents 30% to 50% of current road maintenance costs in Europe.

Table 1 **(Nemry,F., Demirel,H., 2012)** represents a summary list describing the most relevant climate change effects which impact on the transport infrastructure. This table is a part of European Commission's JRC Scientific and policy reports: (i) Impacts of Climate Change on Transport -A focus on road and rail transportt infrastructures; (ii) Impacts of Climate Change -A focus on road and rail transport infrastructures.

Table 1 Weather Events and related Impacts

Weather event	Impacts	
Temperature	· Health and safety problems · Wildfires increase · Tires residues · Thaws floods . Track distortion	· Rutting and potholes · Stress on bridge joints · Durability road infrastructure reduced
Heat waves	· Track distortion . Health and safety problems	
Heavy Rainfall	· Floods · Potholes and blow up's · Slope instability in the abutments · Erosion in retaining walls · Health and safety problems	· Slopes instability · Slopes erosion · Landslides · Insufficient drainage capacity · Poor maintenance of drainage systems
Snowfall	· Freeze-Thaw cycles that stiffen the mixture and crack it · working temperatures delay construction · Durability reduced	· Visibility reduced · Health and safety problems
Windstorm	· Pull out of signalling elements . Overhead line disruption . Bridge closed	
Coastal Flood	· Flooding of the road surface/track · Insufficient drainage capacity · Insufficient drainage systems	
Cyclones	· Flooding of the road/track · Health and safety problems	
Drought	· Durability reduced · Wildfires increase	
Fluvial Flood	· Durability reduced · Health and safety problems · Flooding · Insufficient drainage capacity	· Insufficient drainage systems · Erosion · Overtopping · Reparations
Landslides, etc.		

European Court of Auditors (2012) in their “Contribution of the European Court of Auditors to the EUROSAI-WGEA Coordinated Audit on Climate Change” reference “Impacts of Europe’s changing climate – 2008 indicator-based assessment report performed by the European Environment Agency (EEA) and Joint Research Centre (JCR)", where the need to limit deterioration effects from adverse weather conditions (e.g. prolonged precipitation, heat stress, freeze-thaw cycle) and damaging consequences in case of extreme weather events (e.g. flooding or high rainfall causing an embankment failure) was identified as they are key factor influencing construction designs.

The contribution of weather effects to the ordinary wear and tear of infrastructure and weather disaster risks are indeed intrinsic parameters for transport, energy and telecommunication system design. For instance, bridges constructed over rivers are usually designed to withstand a 100-yr return river discharge. Transport conditions are also highly affected by extreme weather events such as winter storms, ice, and heavy rainfalls.

2.2 Examples of recent regional events

2.2.1 River Flooding in the Danube Catchment

The Danube is the EU's longest river and flows through a number of Central and Eastern Europe countries, including Germany, Austria, Hungary, Croatia, Romania, Bulgaria, Slovakia, Ukraine, Serbia and Moldova. The incidence of flooding on the river appears to be increasing, with major floods reported in 2002, 2005, 2006, 2009, 2010, 2013 and 2014. The 2013 flood was particularly severe and caused major disruption and multiple closures of sections of the rail and road networks across the region,

Figure 1.

Figure 1 Flooding of a motorway junction in June 2013 at Deggendorf, Germany [1]

The increased intense and more regular return period of heavy rainfall events across Europe is leading to an increase in rainfall induced slope failures which can cause severe damage to transport infrastructure,

[1]http://i.dailymail.co.uk/i/pix/2013/06/06/article-2336817-1A2E8B1E000005DC-314_634x430.jpg

Figure 2.

Figure 2 Landslide triggered by a major flood event 2014, Bosnia [2]

2.2.2 Freezing rain Slovenia 2014

In early February 2014, Slovenia and particularly the city of Ljubljana were affected by a particularly harsh fall of snow and freezing rain, Figure 3. The storm had a severe effect on the power grid with some regions suffering complete power outages for two days and loss of mobile telecommunications networks.

Figure 3 Freezing Rain in Slovenia (town of Postojna), November 2013 [3]

[2] http://www.ibtimes.co.uk/balkans-floods-heavy-rain-causes-landslides-bosnia-serbia-1448745

[3] http://www.dailymail.co.uk/news/article-2553989/Slovenia-buried-FOUR-INCHES-black-ice-freak-blizzard-leaves-100-000-without-power-does-66million-damage.html

2.3 Consequence of recent events to the wider region

Whilst specific damage to individual elements of infrastructure is dealt with in the following chapters, this summary highlights some of the regional effects of extreme weather. The recent floods in the Balkans caused widespread damage, with Serbia and Bosnia & Herzegovina being the worst affected countries. According to Wikipedia article "2014 Southeast Europe Floods" the city of Obrenovac in Serbia was extensively flooded, with up to 90% of the area being under water, the municipality of Gunja was hit the hardest in Croatia, and in Bosnia and Hercegovina the River Bosna valley. International Commission for the Protection of the Danube River (ICDR) in their report "Floods May 2014 in the Sava River Basin" report the following numbers: (i) Serbia; 1.6 million affected, 32 000 evacuated, 51 casualties and total damage of 1532 million Euro, (ii) Bosnia and Hercegovina; 1 million affected, 90 000 evacuated, 25 casualties and total damage of 2037 million Euro; (iii) Croatia: 38 000 affected, 15 000 evacuated, 3 casualties and a total damage of 300 million Euro.

Heavy snow, followed by freezing rain and extreme cold, hit Slovenia at the end of January 2014, causing widespread damage to electricity pylons, resulting in many failures and loss of power supply to more than 15% percent of the Slovenian population, cessation of traffic flow on the railway network and severe disruption to the road transport network. Also, nearly half of the national forest stock (500,000 hectares) was badly damaged. The worst hit areas were between 500 and 800 m above sea level. Damage to electricity power lines was set at €27 million plus another €10 million for the power distribution systems. Damage to the state railway was estimated at €20 million and road repairs costs were at least €9 million.

The power cuts in Slovenia led to a state of emergency and the European Commission's Energy Response Coordination Committee (ERRC) activated the Union's Civil Protection Mechanism which coordinated the response of the eleven member states (Austria, Czech Republic, Germany, Croatia, Hungary, Italy, Poland, Romania, Slovakia, Serbia and the United States of America) who offered access to mobile power generation capacity (a grand total of 172 electrical power generators). Several participating states such as Austria, Germany and Croatia responded quickly by sending high capacity electrical power generators.

2.4 Summary

The general effects of major regional weather hazards of the type considered in the RAIN project were described in this section. In the following chapters the effects of hazardous weather events on specific infrastructure elements is considered.

3 Infrastructure

3.1 Bridges

3.1.1 Definition

Transport infrastructure is a foundation stone for any developed economy. For Europe in particular, the single market depends on an effective transport system to bring together people and to facilitate trade within our ever growing economic and political union. Bridges are structures which span and provide passage over physical objects such as a body of water, a valley, a road, a railway line etc. and are one of the most important elements of infrastructure on our road and rail transportation networks. Bridges differ in the manner in which they resist the loads and are selected based on form, purpose and carrying capacity. Bridges can be classified in many different ways, the most common based on the;

- Type of structure (e.g. Slab, beam, arch, truss, suspension, cable stay etc.);
- Material used (e.g. Masonry, steel, concrete etc.)
- Span relationship (e.g. Simple, cantilever, continuous etc.)
- Function (Aqueduct, viaduct, pedestrian, highway etc.)
- Method of connections (e.g. riveted, welded etc.)

Over the years, bridge failures have deeply shocked not only the engineering world but also the general public. Designing and maintaining bridges to resist extreme load effects has always been a safety concern of the bridge engineering community. This concern has been elevated in recent years due to the increased frequency and intensity of extreme weather events.

When a bridge failure or partial failure occurs, the loss of the component can result in much greater consequences than the value of the asset itself. The cumulative damage can include loss of life and injury to many people. Equally the economy can be affected both in the short-term, due to re-routing of traffic or temporary closures, during repairs and in the long term, if reconstruction is required. Therefore, there is a need to investigate engineering solutions to improve the resilience of existing bridges.

3.1.2 Examples of Bridge Failures

Bridges are vulnerable to extreme weather hazards such as floods, tornadoes and wind storms. Results of a study done by Wardhana and Hadipriono (2003) show that the most frequent cause of bridge failure can be attributed to flooding and in particular, the effects of scour. Flash flooding can frequently occur due to intense rainfall in slow-moving thunderstorms which can result in an increased risk of scour of the bridge foundations or inundation of the bridge deck. Scour is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Ultimately the bridge supports can fail due to the reduction in founding material.

Hurricanes, tornadoes, and winter storms can initiate vibration in the bridge, potentially reducing its capacity. Wind gusts can cause harmonic oscillation in suspension bridges or cable stayed bridges as was demonstrated with the failure of the Tacoma Narrows Bridge in 1940. The following paragraphs describe a few examples of bridge failures that have occurred due to extreme weather events.

3.1.2.1 The Bonnybrook Bridge, Calgary, Canada

The Bonnybrook Bridge is a 465-foot-long, 5-span bridge, located in southeast Calgary which spans the Bow River, Figure 4. It is a key element of Canadian Pacific Railway (CP)'s east–west rail network. The original bridge, built in 1897, was a single-track structure that consisted of two 61 m long through-truss spans supported on 2 stone masonry abutments and a stonemasonry pier. The bridge was expanded to accommodate an additional two tracks in 1912, and another bridge for a fourth track was added in 1969.

On the 27^{tH} June 2013, a section of the bridge collapsed, Figure 4, as a result of extreme flooding, during which the flood waters had attacked the shale bedrock/clay pier foundation of the original bridge, eroding and undermining it, resulting in failure of one of the original piers. The flooding had resulted from record rainfalls of 150mm that occurred in a 48 hour period, upstream of the Bow River on the 20th June 2013. As a result, on the 21st June the Bow river reached a peak flow 1740m^3/sec and between the 21st and 24th June the water level was only 20 cm below the underside of the bridge deck, Figure **5**. At the time of collapse, a train carrying petroleum tankers was traversing the bridge. Fortunately, emergency services acted swiftly to prevent loss of any of the contents of the train's cargo.

Figure 4 The Bonnybrook Bridge before the flood [4]

Figure 5 The Bonnybrook Bridge after the flood [5]

3.1.2.2 Calva and Northside Bridge, Cumbria, UK

A period of heavy rain from the 18th to 20th November 2009 brought severe flooding to much of Cumbria in North West England, which also affected southwest Scotland and North Wales. Amongst the worst hit areas in Cumbria were the Derwent and Cocker river valleys, with Cockermouth and Workington suffering the most damage with the flooding of almost 1500 properties (Eden & Burt, 2010). Several old bridges were damaged or collapsed including the Calva Bridge, built in 1840, and the Northside Bridge (1904). On 19th November, the Cocker and Derwent rivers rose to a level that

[4] http://www.spectatortribune.com/wp-content/uploads/1297434976382_ORIGINAL.jpg

[5] http://calgary.ctvnews.ca/polopoly_fs/1.1345363.1376053813!/httpImage/image.jpg_gen/derivatives/landscape_960/image.jpg

flooded much of central Cockermouth. The effect of this water rushing towards Workington destroyed the Northside road bridge, Figure 6 , and the Calva road bridge, Figure 7, which was closed after the main deck was displaced downwards by approximately 30cm and a large crack appeared in the central arch.

Figure 6. Northside Bridge, Workington [6]

Figure 7 Calva Bridge, Workington [7]

3.1.2.3 Tay Bridge, Dundee, Scotland

The Tay Bridge, with a span of 3.5 km, carries the main-line railway across the Firth of Tay in Scotland. The present structure is the second one on the site. The first bridge, a single-track lattice design, opened in 1878 and was noted for its light weight and low cost. Its sudden collapse in high winds on 28th December 1879 was one of the great engineering disasters of history (Scheer 2010). At the time of the collapse, a gale estimated at 80–117 km/hr was blowing down the Tay estuary at right angles to the bridge. The collapse of the bridge, Figure 8, is still the most notorious bridge disaster of the British Isles (Scheer 2010-). The stumps of the original bridge piers are still visible above the surface of the Tay even at high tide.

[6] http://www.dailymail.co.uk/news/article-1233807/Flooded-Workington-united-new-bridge-named-hero-policeman.html
[7] http://www.newsandstar.co.uk/news/uncertainty-as-work-starts-on-flood-damaged-cumbrian-road-bridge-1.718617

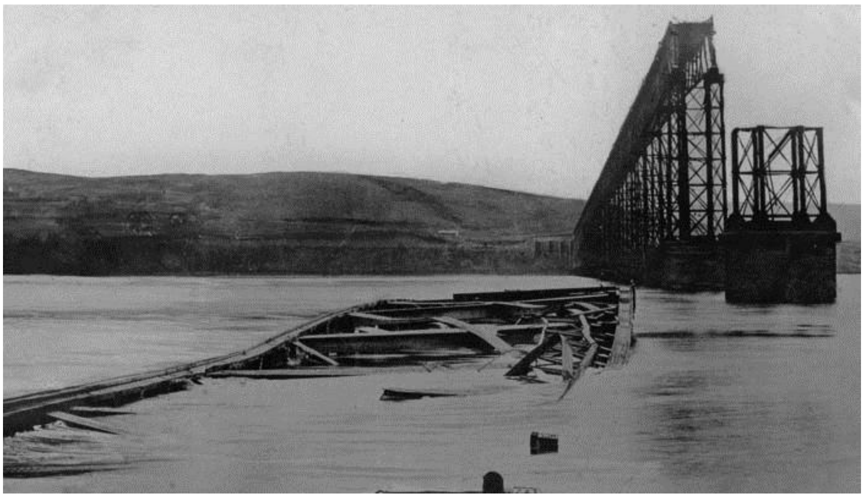


Figure 8 Fallen girders, Tay Bridge [8]

3.1.2.4 Kinzua Bridge, McKean County, United States

The Kinzua Bridge was a railroad bridge, 92 m high and 625 m long and spanned Kinzua Creek in McKean County in the U.S. state of Pennsylvania. The bridge was originally built from iron in 1882 and held the record as the tallest railroad bridge in the world for two years. In 1900, the bridge was dismantled and simultaneously rebuilt out of steel to allow it to accommodate heavier trains. Restoration of the bridge began in 2002, but before it was finished, on July 21, 2003, a tornado struck the Kinzua Bridge, snapping and uprooting nearby trees, as well as causing eleven of the twenty bridge towers to collapse, Figure 9. The failures were due to the failure of the bolts holding the bases of the towers to the concrete anchor blocks embedded into the ground. An investigation determined that the tornado had a wind speed of at least 151 km/h, which applied an estimated 800 kN of lateral force against the bridge (Fleming, 2003). The investigation also hypothesized that the whole structure oscillated laterally four to five times before fatigue started to cause the base bolts to fail. The towers fell intact in sections and suffered damage upon impact with the ground. The state decided not to rebuild the Kinzua Bridge, which would have cost an estimated $45 million.

[8] http://www.nbrstudygroup.co.uk/nbr/tay_bridge.htm

Figure 9 Kinzua Bridge, April 2004 [9]

3.1.2.5 Bridges over the Bejar Ravine, Murcia, Spain

The rains that took place on 27th and 28th September 2012 in the south east of Spain resulted in a flow rate up to 1000 m^3/s in the Béjar Ravine which is located between the towns of Lorca and Puerto Lumbreras (Murcia). This flow rate was close to the theoretical value corresponding to the 500 year flood and caused extensive damage to bridges on the A-7 motorway.

The worst affected bridge was on the Almería-bound main carriageway. The flooding resulted in the scour and collapse of the piers, Figure 10a, and damage to one of the abutments, See Figure 10b. This in turn affected the embankments of access E-2 of the main carriageway and the service road of the carriageway. The collapse of the abutment and piers triggered the collapse of some of the spans, Figure 10c. The flood also affected the backfill of some abutments.

[9] http://www.bradfordera.com/gallery/featured/collection_698536a8-3011-11e0-b51b-001cc4c002e0.html

(a) Pier nº 6 collapsed

(b) Abutment nº 2

(c) General views of Collapsed Structure

Figure 10 Bridge on the Almeira Bound Carriageway [10]

The structure of the Murcia-bound carriageway, together with the two service roads, also experienced damage due to the flood. The pilot-operated piled foundations were barely affected by the flood, however scour of the surrounding soil resulting in removal of the surrounding soil and the piles were exposed to a depth of 2.5 m to 3 m, Figure 11.

[10] Courtesy of Dragados

Figure 11 (a) Bed material scoured downstream of the structure

(b) Piles scoured to depths of 2.5m - 3m[10]

At the embankments and bank access to the structure, as result of the erosive action of the water, severe scour occurred under the run-on slab of Abutment 2 of the structure corresponding to the main Murcia-bound carriageway of the motorway, Figure 12. To compound this, the erosion of the closest access embankments, produced by the collapse of the adjacent abutment, and the erosive action of water, has an additive effect. The combined effects of both action produced a high uncertainty of geotechnical and structural behaviour of the access embankment which prevented the immediate restoration of the traffic.

Figure 12 General view and detail of the abutment nº 2 of the Murcia-bound carriageway and scour of the run-on slab [10]

3.1.3 Potential Impacts

Floods cause bridge damage in different ways. In a flood, not only does the level of the water around the bridge rise but the speed of flow increases. Trees and other debris picked up in the flood waters can be carried downstream and accumulate upstream of the bridge, underneath it or even over it. This debris applies an additional load to the structure and presents an increased surface area for hydrodynamic loads to be applied to the bridge. As a result the pressure on the bridge can either push it downstream or even lift it up off its foundations. Equally, the debris reduces the cross sectional area of the flow at the bridge, the water height upstream of the bridge and the water speed around the bridge supports increases. This increased water speed can result in scouring of the river bed underneath and around the bridge supports.

Extreme wind speeds are induced by strong horizontal pressure gradients and occur in association with both extra-tropical cyclones, i.e., low pressure systems such as winter storms, and thunderstorms. On larger scales, the key variable for strong winds is the horizontal pressure gradient, associated with the prevailing synoptic systems. On a local scale, the wind speed may be further enhanced or reduced by orographic features and the land use in terms of surface roughness.
In general, it is not the mean wind speed that is responsible for most of the damage, but the wind gusts, which are the manifestation of atmospheric turbulence. Wind gusts are sudden and short-term increases in wind speed with durations of the order of seconds or shorter.
The high speed winds can contribute to bridge failure by increasing the potential for debris impacts and facilitating large wave surges. Additionally, there have been several examples of structural damage to operator houses or machinery housing on movable bridges, and damage to electrical cables on some towers. The houses and control rooms, however, often suffer a combination of damage resulting from water inundation, impact, or debris.

3.1.4 Remediation measures which increase resilience

As detailed, a leading cause of bridge failure is bridge scour, which occurs when rapidly moving water erodes the riverbed soil around the bridge supports. There are a number of ways to minimise the effects of scour. If possible, the bridge should consist of a single span, thus reducing the need for supports in the water. However typically, the majority of bridges will require multiple supports along the span. In these cases, the abutments should be well protected below and above normal water levels to prevent erosion of the founding material. If the bridge is on a wide flood plain, the bridge deck and the abutments should be higher than the surrounding land, with a ramp up at both ends, and in this way the flood is relieved by going around the bridge.
Using a protective system, such as 'riprap', is one of the common methods to control the scour. Placing a riprap layer locally around the pier increases the resistance, and scouring around the pier can be prevented. Recent developments include a system which is designed to dissipate energy and resist the erosive forces of flowing water, protecting channel boundaries from scour and erosion Figure 13 and Figure 14.

Figure 13 ArmorFlex erosoin protection [11][11]

Figure 14 A-Jacks scour protection system [12][12]

[11] http://www.conteches.com/products/erosion-control/hard-armor/armorflex.aspx
[12] http://www.conteches.com/products/erosion-control/hard-armor/a-jacks.aspx

In the case of bridge deck inundation, one remediation option is to ensure the deck is above the level of the flood. This can be achieved by 'raising' the bridge deck, a process whereby the bridge is lifted from its supports by powerful jacks. Invariably this will require the installation of new bearings. Equally this process can apply to the repair or replacement of damaged bearings (Figure 15).

In providing resilience against wind loading, a number of options are available to the engineer. One such method is to ''stiffen'' the bridge by the addition of cables and stays or stiffening existing girders. The Deer Isle-Sedgwick Bridge, Figure 15, is an example of a bridge that has been modified a number of times since its construction in 1939 due to concerns over the impact of wind loads. Initially, due to concerns over its 'instability' when subjected to wind loading a system of stay cable stays and floor stays were added to stiffen the girders. Subsequently, in the early 1990's, lightweight fibreglass fairings, were attached to the side of the main girders in order to provide further resilience against the wind. The fairings are triangular pieces that, in effect, ''slice'' the wind and ensure the air flows around the bridge smoothly (i.e. less eddies etc.).

Figure 15 Installation of a RESTON-SPHERICAL UPLIFT bearing under bridge's raised deck[13]

Figure 16 Deer Isle-Sedgwick Bridge and fairings designed in the FHWA [14]

Dampers can also be used to improve bridge resilience in order to mitigate against wind-induced cable vibrations. Figure 17 shows one of several types of dampers deployed on the Arthur Ravenel Jr. Bridge in South Carolina. A trussed support frame is anchored to the deck, and two pairs of viscous dampers are fastened to the top of the frame.

[13] http://www.mageba-germany.de/en/804/References.htm?Reference=45055
[14] http://www.historicbridges.org/bridges/browser/?bridgebrowser=maine/deerisle/

Figure 17 Ravenel Jr. Bridge in South Carolina and dampers [13]

3.2 Pavements

3.2.1 Definition

The pavement is the hard layered structure that forms a road carriageway. Its function is twofold; (a) to effectively dissipate the traffic loads when reaching the existing natural surface and (b) to drain and to protect from the effects of frost. Basically, the pavement types can be classified into two groups, flexible and rigid. Flexible pavements are those which are surfaced with bituminous (or asphalt) materials. Rigid pavements are composed of a PCC (Portland Cement Concrete) surface course and can have reinforcing steel, which is generally used to reduce or eliminate joints.

Flexible pavements generally require maintenance or rehabilitation every 10 to 15 years. Rigid pavements, on the other hand, can often serve 20 to 40 years with little or no maintenance or rehabilitation. Therefore rigid pavements are often used in urban, highly trafficked areas. Nevertheless, flexible pavements are generally less expensive and quicker to produce than rigid pavements.

The typical flexible pavement structure consists of:

- Surface course: This is the top layer that comes in contact with traffic. It may be composed of one or several different Hot Mix Asphalt (HMA) sublayers. It provides characteristics such as friction, smoothness, noise control, rut and shoving resistance and drainage. In addition, it serves to prevent the entrance of excessive quantities of surface water into the underlying layers. This top structural layer can be subdivided into the wearing course (the upper layer) and the intermediate/binder course. The most common types of HMA pavements are dense-graded HMA, stone matrix asphalt (SMA) and open-graded HMA.

- Base course: This is the layer directly below the surface course and generally consists of aggregate (either stabilized or unstabilized) or HMA. It provides additional load distribution and contributes to drainage and frost resistance.

- Subbase course: This is the layer (or layers) under the base layer. A subbase is not always needed. It functions primarily as structural support but it also minimises the intrusion of fines from the subgrade into the pavement structure, improves the drainage and minimises the frost action damage.

The typical rigid pavement structure consists of:

- Surface course: This is the top layer, which consists of the PCC slab. It provides characteristics such as friction, smoothness, noise control and drainage. Three major categories can be differentiated by their means of crack control; (a) Jointed plain concrete pavement (JPCP), which controls cracks by dividing the pavement up into individual slabs separated by contraction joints. JPCP does not use any reinforcing steel but does use dowel bars and tie bars. (b) Jointed reinforced concrete pavement (JRCP), which controls cracks by dividing the pavement up into much larger individual slabs separated by contraction joints. JRCP uses reinforcing steel within each slab to control within-slab cracking. (c) Continuously reinforced concrete pavement (CRCP), which uses reinforcing steel rather than contraction joints for crack control.

- Base course. This is the layer directly below the PCC. It provides additional load distribution, contributes to drainage and frost resistance, uniform support to the pavement and a stable platform for construction equipment. Bases also help prevent subgrade soil movement due to slab pumping. Base courses are usually constructed out of aggregate base, stabilized aggregate or soil, dense-graded HMA, permeable HMA, or lean concrete.
- Subbase course. This layer is equivalent to the one presented in the case of the flexible pavement.

Equally, drainage systems must be considered, which are essential for the proper performance of the road. The most noteworthy are:

- Table drains, which are located within the verges in cuttings. Their purpose is to collect surface water draining from the carriageway and adjacent cut batter, carrying the water to a suitable point of discharge beyond the cutting.
- Catch drains, which are located on the high side of cutting slopes behind the batter rounding. Their purpose is to intercept the flow of surface and seepage water within the upper soil layer to prevent erosion of the batter face. In areas where the catch drain is susceptible to scour, the surface water should be intercepted using a catch bank placed on the natural surface on the high side of the batter point.
- A dyke, which is a low, longitudinal mound of earth, asphalt or concrete, provided near the edge of embankments when it is required to protect the batters from erosion, by controlling the water movement off the road pavement surface. It is located under the guard fence on the lower side of the pavement cross-fall.
- Batter drains, which are provided on embankments to transport the water from dykes to the bottom of the batter.
- Channels, which are used to collect and convey surface drainage to a discharge or collection point.

3.2.2 Examples of Failures

When an extreme weather event occurs, the pavement of the road network is often damaged. Nevertheless, only damage resulting in a complete loss of functionality of the road is generally reported. To illustrate this point, three cases of distress of the pavement are shown. All of them have taken place in the last 15 years around Europe, namely (a) damage to A9 Raigmore Slip Road, Inverness (Scotland), due to the heavy rainfall in 2002,Figure 18; (b) damage to a road in Kerry

(Ireland) due to a windstorm and heavy rainfall in January 2014, Figure 19); and (c) damage to A-139 Benasque-Cerler (Spain) due to Ésera river flooding in June 2013,Figure 20.

Figure 18 Damage to A9 Raigmore Slip Road, Inverness (Scotland), 2002, following heavy rainfall. Photograph courtesy of BEAR Scotland Ltd. [15]

Figure 19 Damage to a road in Kerry (Ireland) due to a windstorm and heavy rainfall, January (2014). Photograph courtesy of radiokerry.ie [16]

Figure 20 Damage to A-139 Benasque-Cerler (Spain), June 2013, due to Ésera river flooding. Photograph courtesy of Heraldo.es [17]

[15] Photograph courtesy of BEAR Scotland Ltd.
[16] Photograph courtesy of radiokerry.ie

3.2.3 Potential Impacts

Initially, the most important types of failure or distress of pavements are defined. Subsequently, the relation between these distresses and the extreme weather phenomena is established. Two scenarios are considered, namely, where (a) the climatological phenomena are the direct cause and (b) the climatological phenomena are the indirect cause. In relation to this classification, later on, the effects are divided into direct (damage caused only due to a given hazard) and indirect (combination of conditions together with a given hazard are required in order to damage the pavement).

The pavement can suffer multiple kinds of distresses. The most highlighted distresses of the flexible and rigid pavement associated with climatological events are the following:

<u>Bleeding or flushing</u>: a shiny, black surface film of asphalt appears on the road surface caused by upward movement of asphalt in the pavement surface. It can be caused by hot weather.

<u>Thermal cracking</u> (transverse cracking): a series of cracks evenly spaced perpendicular (transverse) to the flow of traffic. There are two types of thermal cracks - those occurring during a single falling temperature event (i.e. ice storm), and those caused from damage accumulated after repeated temperature cycling. Cracks appear usually over the entire pavement, not just in wheel paths. It is not an indication of structural failure. It can be caused by sharp temperature drops.

Figure 21 Thermal cracking [18]

<u>Premature aging surface</u>: Minimal visual signs of distress on the surface. The underlying structure remains in good condition. This type of distress can be caused by exposure of the pavement, over time, to both traffic and environmental factors (e.g. weather etc.)

[17] Photograph courtesy of Heraldo.es
[18] http://www.roadscience.net/

Figure 22 Premature aging surface [18]

Longitudinal Cracking (Wheel Path Cracking): Cracking in the direction of flow of traffic, usually at the edge of wheel paths. It can be caused by heavy traffic and an unstable base.

Figure 23 Longitudinal Cracking [18]

Rutting: Permanent deformations of the pavement (indentations) in the wheel paths, which can lead to cracking and further deterioration. It can be caused by heavy traffic and extreme temperatures.

Figure 24 Rutting [18]

Fatigue cracking (Alligator cracking): Interconnected cracking with a pattern resembling alligator skin. It is typically found in wheel paths and may be accompanied by rutting. It can be caused by accumulated damage, age hardening, and poor drainage.

Figure 25 Fatigue cracking (Alligator cracking) [18]

Potholing: Holes in pavement usually formed when water gets into cracks and destroys the underlying structure. It can be caused by accumulated damage, age hardening, and poor drainage.

Figure 26 Potholing [18]

Ravelling: Loose materials (usually aggregate) that “ravel” from the surface or edges of the pavement, resulting in depressions which may fill with moisture and loose aggregate which may pose problems. It can be caused by snowplough damage, and intensive traffic.

Figure 27 Ravelling [18]

Bumps and sags: Small, localized bulges and small, abrupt depressions of the pavement surface, respectively. They can be caused by buckling or bulging of underlying PCC slabs or frost heave.

Edge cracking: Cracks along the edge of the pavement near the shoulder. Cracks can be caused by inadequate support, sub-base failure due to water intrusion, and traffic loading.

Oxidation: Surface of the pavement becomes light grey, causing binder to become brittle. It can be caused by ultraviolet rays from the sun and exposure to water.

Pocking: Individual pieces of aggregate have dislodged from the pavement surface and left small voids. In some cases, the asphalt binder becomes hard and brittle from oxidation, allowing the stone to break away. In other cases, some pieces of aggregate may expand or prematurely deteriorate and work out of the pavement under traffic or snowploughing.

Spalling: Cracking, breaking or chipping of joint/crack edges. Usually occurs within about 0.6m of joint/crack edge. It can be caused by (a) infiltration of incompressible materials and subsequent expansion, (b) disintegration of the PCC from freeze-thaw action, and (c) heavy traffic loading.

Faulting: A difference in elevation across a joint or crack usually associated with un-doweled joints. It is a result of slab pumping.

Pumping: Is the movement of material underneath the slab or ejection of material from underneath the slab as a result of water pressure. Water accumulated underneath a PCC slab will pressurize when the slab deflects under load. It can lead to linear cracking, corner breaks and faulting. It is caused by a high water table, poor drainage, and panel cracks or poor joint seals that allow water to infiltrate the underlying material.

Punchout: Localized slab portion broken into several pieces, due to moisture infiltration leading to erosion of base/subbase support. It can be caused by steel corrosion, excessively wide shrinkage cracks or excessively close shrinkage cracks.

Durability cracking: Series of closely spaced, crescent-shaped cracks near a joint, a corner or a crack. It is caused by freeze-thaw expansion of the large aggregate within the PCC slab.

Collapse due to failure of lower layers: Lost of stability of the lower layers causing the collapse onto pavements.

Extreme Climatological events can affect directly the state of pavements. The most harmful events seem to be the floods and heavy rainfalls, where the capacity of existing drainage systems is exceeded and the moisture balances can be altered, resulting in structural problems. Moreover, the coastal floods are dangerous because the high water tables reduce the structural strength of pavements. On the other hand, as the bituminous surface treatments are affected by the temperature and the high temperatures deteriorate seal binders, wild fires too can be critical events.

A more detailed relation of the impacts of extreme weather events on flexible and rigid pavement is given in Table 2. It is noted that an event can cause direct damage (indicated as “direct” in the fourth column), or contribute to the damage being needed other factors to develop the distress (indicated as "indirect" in the fourth column).

Table 2 Direct impacts of extreme weather events on flexible and rigid pavement.

DIRECT IMPACTS			
TYPE OF PAVEMENT	TYPE OF DISTRESS	CAUSES	EFFECT
Flexible	Bleeding or flushing	Forest Fires	Direct
Flexible	Bumps and sags	Icing, Snowfall and Snow Storms, Snow Loading	Direct
Rigid	Durability Cracking	Icing, Snowfall and Snow Storms, Snow Loading	Direct
Flexible and rigid	Edge cracking	River Floods, Coastal Floods, Landslides	Direct
Flexible	Fatigue cracking	River Floods, Coastal Floods	Indirect
Rigid	Faulting	River Floods, Coastal Floods, Landslides	Indirect
Flexible and rigid	Longitudinal Cracking	River Floods, Coastal Floods, Landslides	Indirect
Flexible	Oxidation	River Floods, Coastal Floods, Heavy Rainfall	Direct
Flexible	Pocking	Snowfall and Snow Storms, Snow Loading	Indirect
Flexible	Potholing	River Floods, Coastal Floods, Tornadoes, Hail, Heavy Rainfall	Indirect
Flexible	Premature aging surface	Tornadoes, Hail, Heavy Rainfall, Coastal Floods, River Floods, Landslides, Snowfall and Snow Storms	Indirect
Rigid	Pumping	Heavy Rainfall, River Floods, Coastal Floods, Landslides	Direct
Rigid	Punchout	Coastal Floods, River Floods	Indirect
Flexible	Ravelling	Snowfall and Snow Storms, Snow Loading	Indirect
Flexible	Rutting	Forest Fires, Snowfall and Snow Storms	Indirect
Rigid	Spalling	River Floods, Coastal Floods, Icing, Snowfall and Snow Storms	Direct
Flexible and rigid	Thermal cracking	Forest Fires, Icing, Snowfall and Snow Storms	Direct
Flexible and rigid	Collapse of lower layers	River Floods, Coastal Floods, Landslides	Direct

The indirect impacts of extreme climatological events on pavements are due to the effects on the human activity and location of population modifying the demand for roads (rate and proportion of heavy freight vehicles). The frequency and the intensity of the extreme weather events on a specific area can lead population to migrate to perceived safer regions. This perception of the regional safety level also affects the Tourist Industry, which is an important attractor of traffic demand. Other economic activities significantly affected are Agriculture and Livestock farming. The corresponding negative consequence on roads is summarized in Table 3.

Table 3 Indirect impacts of extreme weather events on flexible and rigid pavement.

INDIRECT IMPACTS			
INDIRECT CAUSE	**CONSEQUENCE OF THE INDIRECT CAUSE**	**DIRECT CAUSE**	**EFFECT**
Frequent extreme weather events	Variation of the rate of population	Variation of the traffic demand (rate and proportion of heavy freight vehicles)	Premature aging surface, Longitudinal, Thermal and Edge Cracking, Rutting, Spalling
	Variation of Tourist Industry		
Mainly: Heavy Rainfall, Icing, Hail, Forest Fires, Windstorms, Coastal Floods, River Floods	Variation of Agriculture and Livestock farming		

3.2.4 Remediation measures which increase resilience

The measures to increase resilience of pavements can be classified in three levels;

Design level: it is important that drainage systems are designed to meet the required performance level. It is recommended to revise the parameters for the design storm is those areas with high probability of extreme rainfall. Moreover, to reduce the climatic effects, a proper selection of materials has to be carried out, taking into consideration the probability of occurrence of these events and the importance of the roadway.

Maintenance level: with the aim of minimizing the damage of the pavements, it is important to prevent moisture from entering the crack and damaging the underlying structure. Routine and periodic maintenance activities, such as pothole patching, kerb and channel cleaning, patching, surface correction and resealing (require surface dressings/reseals) will be much less expensive than later corrective maintenance or rehabilitation. Special attention has to be paid in the structural elements such as embankments and protection elements.

Rehabilitation level: before the level of distress leads to the collapse, activities such as chipseal, resheeting and asphalt overlays, depending upon the pavement type, can prolong the life of the roads.

3.2.5 Processes and Technology

Chemical technology: Asphalt additives, emulsifiers and other chemicals added directly to the asphalt mix during its production, are used to give the asphalt more desirable qualities. In general, elastomers provide the asphalt with more resiliency and flexibility, while plastomers result in mixes with higher stabilities and stiffness moduli. The results are highly dependent upon the concentration, the molecular weight, the chemical composition, and the molecular orientation of a particular polymer as well as the crude source, the refining process and the grade of the base asphalt used (http://www.roadscience.net). These products can make up a composite section over PCC, or an interlayer between HMA layers and then as a flexible surface overlay. More precisely, some products are especially designed for reducing traffic disruption caused by snow and ice. These additives lower the freezing temperatures of water on the road surface by disturbing the formation of ice crystals which don't adhere to the pavement surface, allowing for easy removal by means of conventional street cleaning equipment (http://www.coldlay.co.uk/winterpave.cfm).

Processes: Several common procedures exist to maintain and rehabilitate pavements according to the degree of damage, Figure 28. A detailed explanation of these processes is given bellow.

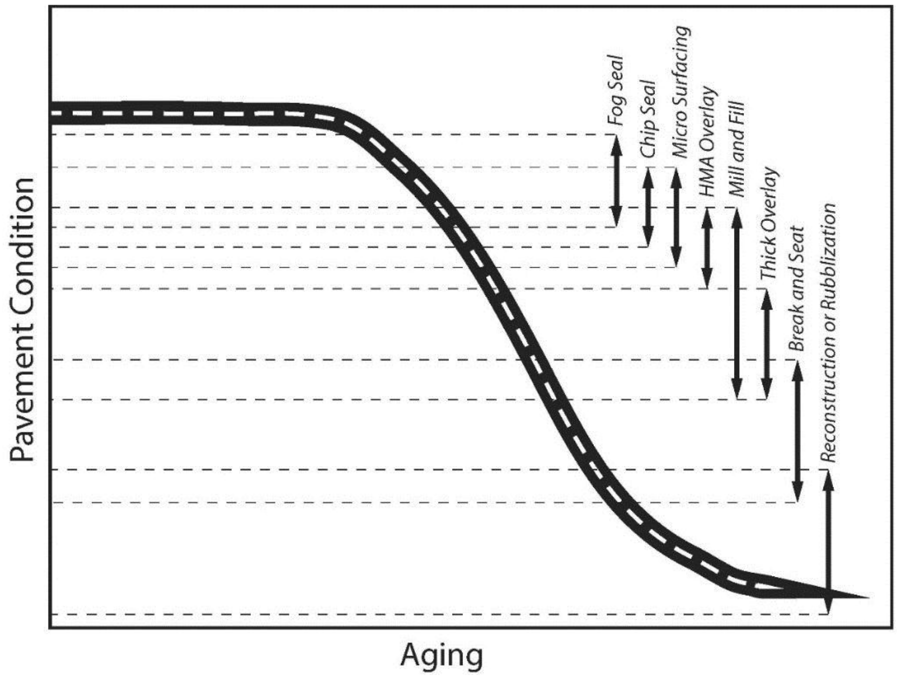


Figure 28 Common procedures to maintain and rehabilitate pavements according to their degree of damage[18]

Fog seal is a preventive maintenance consisting of a light application of a diluted slow-setting asphalt emulsion to the surface of an aged (oxidized) pavement surface. Fog seals are low-cost and are used to restore flexibility to an existing HMA pavement surface. They may be able to postpone the need for a BST or non-structural overlay for a year or two. An excessive application rate may result in a thin asphalt layer on top of the original HMA pavement. This layer can be very smooth and cause a loss of skid resistance.

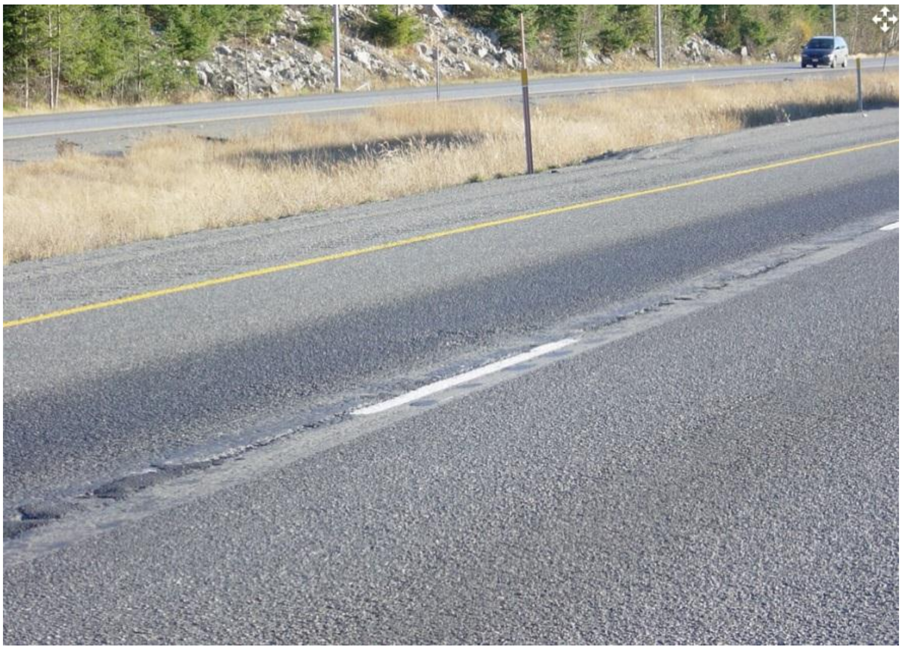


Figure 29 Maintenance patch on a longitudinal joint covered by a fog seal[19]

Chipseal (Bituminous surface treatments) is a technique used to create a stand-alone drivable surface on a low volume road, or rehabilitate an existing pavement. It is constructed by spraying a layer of emulsified asphalt, and placing a layer of aggregate on top. These treatments can be applied directly to a base course, or on existing asphalt pavement structure, and represent a low cost alternative to typical asphalt paving. Chip seals should only be used to rehabilitate minor distresses on a roadway, such as worn surfaces, ravelling, and small cracks. They will likely perform inadequately when cracks become too wide or the pavement has undergone significant structural deformation. Before constructing a chip seal, any major deficiencies must be corrected in the existing structure (repairing the alligator cracks or patching the potholes). Next, the surface should be swept to remove particles that could interfere with bonding of the asphalt and the existing pavement. After the asphalt and aggregate have been placed, chip seals are compacted similar to hot mix asphalt pavements. Following compaction, it is important to keep traffic off of the new surface until moisture content has reached an acceptable level. Allowing traffic to use the road prematurely can result in the loss of particles from the pavement surface.

[19] http://www.pavementinteractive.org/

Micro surfacing, Figure 30, consists on applying a homogenous mixture of emulsified asphalt, water, well-graded fine aggregate, mineral filler and advanced polymer additives. It is used to fill existing pavement surface defects as either a preparatory treatment for other maintenance treatments or as a wearing course.

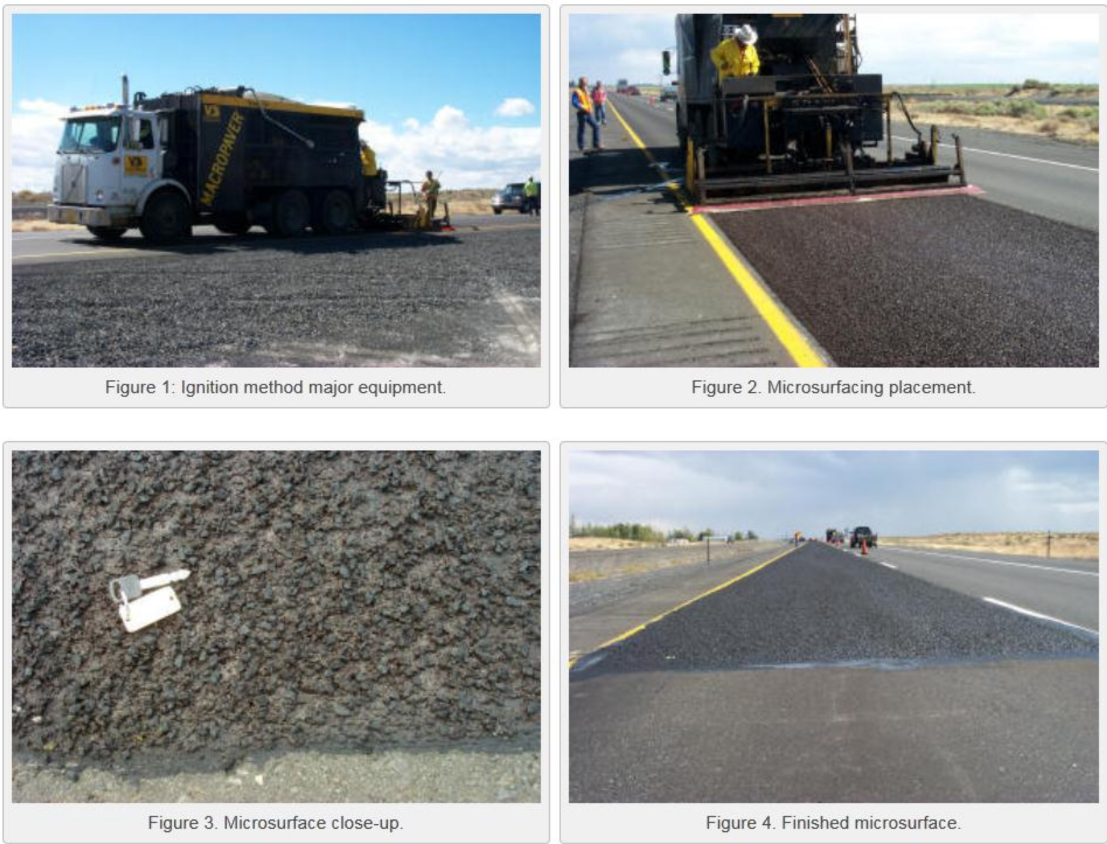


Figure 1: Ignition method major equipment.

Figure 2. Microsurfacing placement.

Figure 3. Microsurface close-up.

Figure 4. Finished microsurface.

Figure 30 Application of microsurfacing slurry [19]

Structural overlays, such as Portland Cement Concrete (PCC) or Hot Mix Asphalt (HMA), over an existing pavement structure. This is different than a total replacement of the structure, and is typically done when there is only minor to modest damage to the existing pavement structure. When constructing an overlay, the old surface is typically milled or ground off, repairing any minor structural deficiencies. Finally, a new surface is applied. This operation is used to increase pavement structural capacity.

Milling and filling. Milling, also called grinding or cold planning, is used to remove a distressed surface layer from an existing pavement. The depth of the intervention will depend on the degree of the damage. Milling machines are generally used to remove the top layers. Afterwards, the surface is cleaned off by sweeping or washing to prevent the dirt and dust decreasing the bond between the new overlay and the existing pavement. Finally, new layers are built according the new requirements.

Figure 31 Asphalt road being milled [20]

Crack/break and seat involves breaking the underlying PCC pavement into relatively small pieces (on the order of about 0.3 m^2 to 0.6 m^2) by repeatedly dropping a large weight, Figure 17. The pieces are then seated by 2 to 3 passes of a large rubber tired roller. The result is a pavement made of small firmly-seated pieces. This technique is used to prevent, or at least delay, the onset of reflection cracking in the HMA overlay caused by the large differential movement at slab and crack interfaces.

Figure 32 Drop hammer [19]

[20] https://upload.wikimedia.org/wikipedia/commons/thumb/4/48/Road_repaving.jpg/400px-Road_repaving.jpg

Rubblization involves reducing the underlying PCC pavement to rubble. This rubble is then used as a high quality base course to support the HMA overlay. Rubblizing is typically done with one of the following two pieces of equipment; (a) resonant pavement breaker, which strikes the rigid pavement at low amplitude with a small plate at the resonant frequency of the slab; and (b) multi-head breaker (see Figure 33), which uses a series of independently controlled high amplitude drop hammers to smash the slab. Typically, there are between 12 and 16 hammers. This technique, as that presented before, is used to prevent, or at least delay, the onset of reflection cracking in the HMA overlay caused by the large differential movement at slab and crack interfaces.

Figure 33 Multi-head breaker [19]

3.3 Cuttings and Embankments

3.3.1 Definition

Cuttings and embankments are one of the most common elements of road and rail transport networks. Failures in slopes (either natural or man-made) have a direct impact on road and rail infrastructure, disrupting traffic, causing economic losses as a result of the cost of reinstatement, delays and can result in casualties and fatalities.

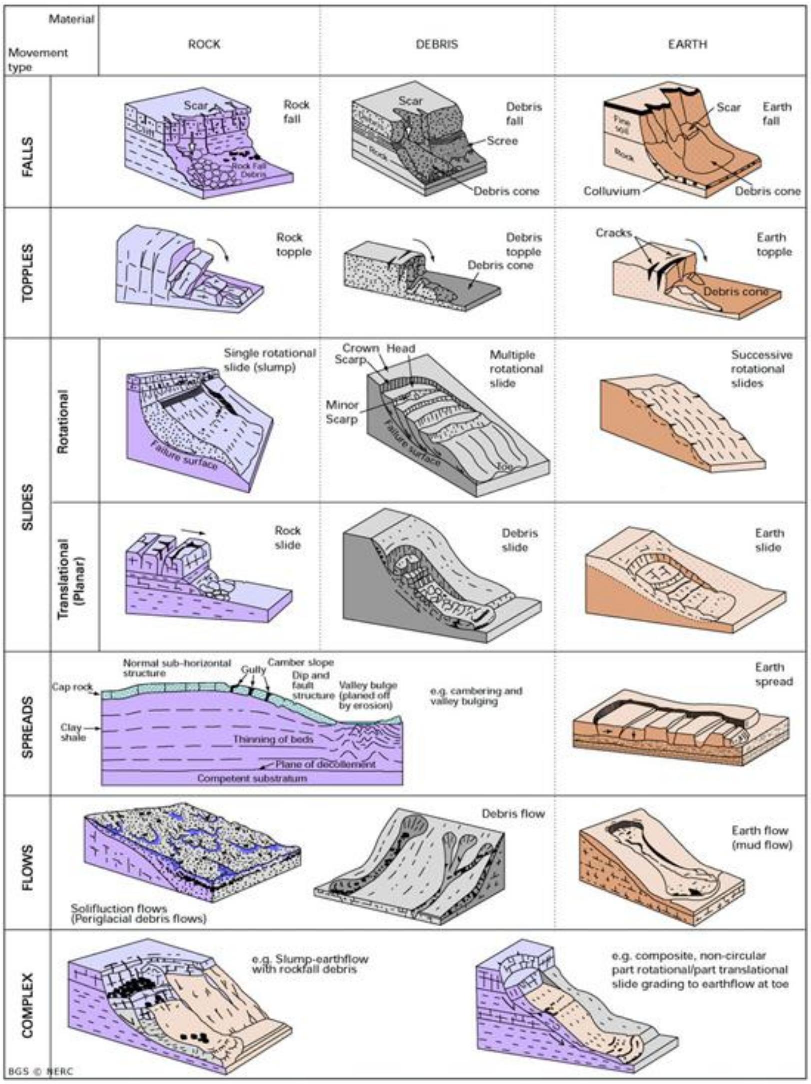


Figure 34 Landslide types[21]

Landslides are defined as gravitational movement of rock mass, earth or debris down a slope Cruden (1991), which are basically described by two characteristics: (1) material involved (rock, debris,

[21] http://www.bgs.ac.uk/landslides/how_does_BGS_classify_landslides.html

earth) and (2) the type of the movement (falls, topples, slides, spreads, flows), Cruden and Varnes, (1996). The range of different types of slope failures commonly encountered is shown in Figure 34.

The occurrence and reactivation of landslides are influenced by a number of contributory factors related to bedrock and soil properties, including slope morphology, relief energy and land use. In Europe, most catastrophic landslides are associated with heavy/or prolonged rainfall, coupled with soil erosion on mountain slopes (EEA 2010). Other important triggering factors include earthquakes, snow melt and slope toe erosion by rivers or sea waves, thawing of mountain permafrost, volcanic eruption, and man-made activities such as slope excavation and loading, land use changes, blasting vibrations or water leakage from utilities Hervas (2003).

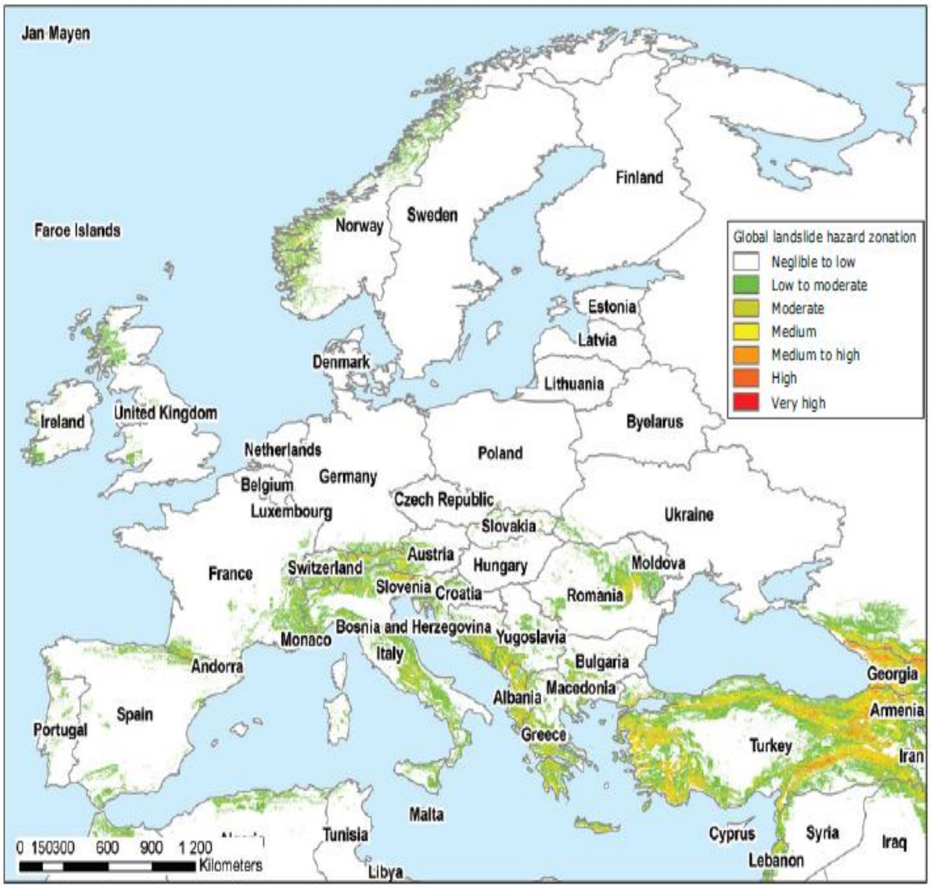


Figure 35 Global landslide hazard zonation according to NGI, 2009[22]

The distribution of landslide hazards in Europe, Figure 35, is primarily linked to mountainous areas (e.g. the Alps, Scandinavian Peninsula, Balkans, etc.). However, according to several IPCC (Intergovernmental Panel on Climate Change) reports there has been an increase in the mean temperature and alteration in precipitation patterns over the last 50 years, due to climate change, which has an impact on slope stability. More changes are expected in the future, creating bigger gaps between the Mediterranean region (which is predicted to experience a decrease in

[22] *EEA* (2010): Technical Report No 13/2010- Mapping the impacts of Natural Hazards and Technological Accident in Europe

precipitation) and Central and Northern Europe (with increases in precipitation). According to Xue and Gavin (2007), rainfall is one of the biggest triggers for translational landslides on natural and man-made slopes. Hence with increased rainfall duration and intensity all transport networks and particularly railways which were mostly constructed in the mid 1800's are liable to be prone to substantial risk of landslides.

3.3.2 Examples or recent slope failures on transport networks

3.3.2.1 Hatfield Colliery landslip

The UK Rail Accident Investigation Branch (RAIB) reported on a major slope failure that occurred on the 11th of February 2013, in Hatfield Colliery, in South Yorkshire. The landslide resulted in major deformation to the rail track**,** Figure 36. The initial movements were noted a couple of days before so there were no damage to trains and no injuries. However major works were required to remediate the track and traffic was not reopened until the 6th of July 2013.

Figure 36 Rail track deformations in Hatfield Colliery [23][23]

According to aerial photos taken by Network Rail, Figure 37, the track deformation happened due to a large landslip caused by spoil tip located outside the railway boundary, and within Hatfield Colliery (coal mines).

[23] *RAIB-Rail Accident Investigation Branch* (2014): Rail Accident Report 2014

Figure 37 Aerial view of the landslide [23]

The slope was visually examined in November 2009 and was categorised as serviceable, therefore requiring no further specialist consideration until the next routine examination due after a period of 10 years. The original geometry and the slope following failure are shown in Figure 38. The tracks were located at the toe of the landslip. The failure which occurred in February, near the end of the winter is a good example where monitoring and visual assessment along the track itself would have offered no warning of the failure which initiated in land adjacent to the rail line.

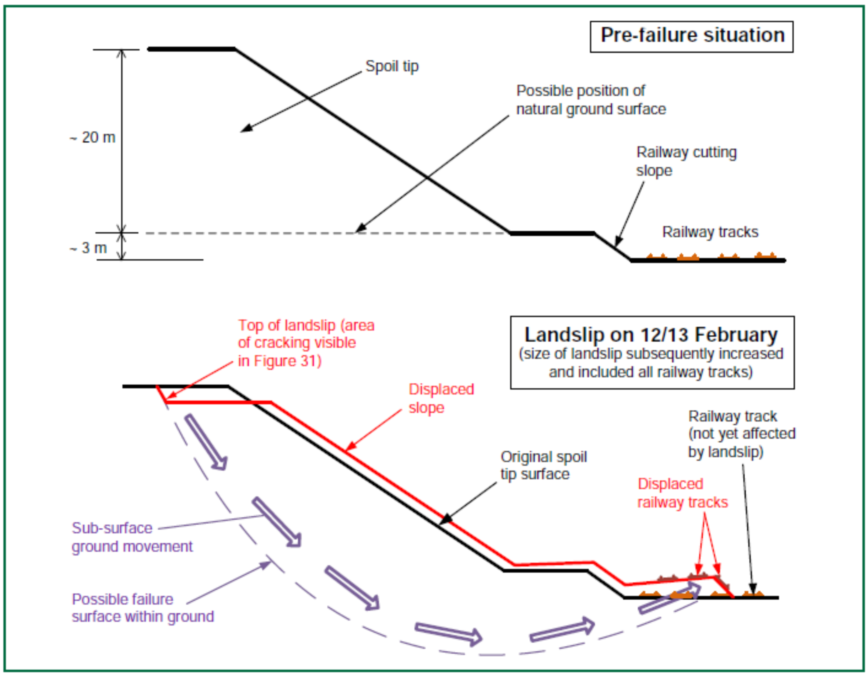


Figure 38 Hatfield Colliery landslide geometry [23]

3.3.2.2 Makarska rockfall

The entire Mediterranean coast line is subject to frequent rockfalls which occur in limestone slopes, and very often those rock falls have an impact on transport infrastructure. They are frequently caused by weathering of the limestone in combination with heavy rainfall and artificial influences during the construction of highways (Arbanas, et al. 2012).

Figure 39 Rock fall near city of Makarska [24]

A major rock fall occurred on the regional road D-512 Makarska-Vrgorac, in Croatia on the 24th of October 2010, Figure 39. Prior to the large rockfall, smaller boulders were displaced and the road was cleared and warning signs were erected. The location had suffered a major rockfall two decades before. The boulder shown weighed several thousand tons, however due to the earlier occurrence of smaller rockfall, the road was not operational and nobody was injured. A survey of the rock surface determined that major remediation was required to the area. The slope was so unstable that an alternative route requiring the construction of a two lane road tunnel, Figure 40, was constructed, in order to bypass the critical area. Reinforced concrete galleries were constructed at each end of the tunnel along with rockfall nets and drapes accompanied by monitoring devices.

[24] http://www.slobodnadalmacija.hr/Hrvatska/tabid/66/articleType/ArticleView/articleId/119360/Default.aspx

(a)

(b) (c)

Figure 40 (a) rockfall nets and shortcrete covers, (b) drapes (c) tunnel bypassing a critical road segment [25]

[25] http://www.hupg.hr/file/DPG2011/Dan%201/DPG2011_01_Kovacevic.pdf

3.3.2.3 Landslide on a motorway in Taiwan 2010

Although not located in Europe, this landslide shows the impact of a landslide on road infrastructure and human lives, Figure 41. The landslide occurred in late April 2010, and covered a 300 m stretch of motorway in Taiwan. A grand total of 50 excavators and 100 trucks were mobilised to search for survivors.

Figure 41 Landslide on a motorway in Taiwan 2010 [26]

[26] http://www.dailymail.co.uk/news/article-1268861/Search-female-taxi-driver-car-vanished-GPS-location-mystery-landslide.html

3.3.3 Potential Impact

Landslides/rockfalls are mostly caused by gravity acting on a weakened layer of soil/block of rock. Activities which trigger the landslides/rockfalls can be natural or human-related activities which lead to instabilities. In the majority of cases of soil slope failure within a transport network, the failure is initiated (primarily) by rainfall and a change in water conditions caused by extreme events such as floods. During rapid drawdown after a flood, there is a change in hydrostatic pressure acting on the slope surface, leading to changes in total stresses and pore pressure inside the slope, influencing the stress-strain relationship in the soil skeleton. In temperate climates seasonal variations in temperature can lead to slight variations in the water table (these changes are much more significant in tropical climates). Periods of hot weather can lead to desiccation and near-surface cracking. Subsequent rainfall thus has a natural flow-path which may penetrate and saturate the soil at depth.

Larger differences in temperature values, in winter seasons or mountainous areas, lead to freeze-thaw weathering (various types of mechanical weathering). One of the traditional explanations for frost weathering is volumetric expansion of freezing water. By freezing into ice water increases its volume by 9%. The turning point from liquid state into solid state for water is -4^{o}C, but at -22^{o}C, ice growth can generate pressures up to 270MPa, and that is more than enough to fracture any rock. Less influential are windstorms, which can lead to erosion of the soil or removal of vegetation which has a stabilising effect on the slope.

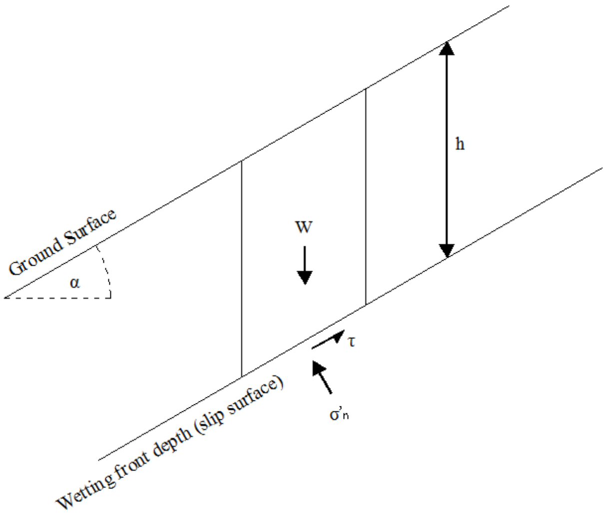


Figure 42 Development of the wetting front in a slope during rainfall [27]

One of the possible intensity measures used to predict the likelihood of rainfall induced landslides is the wetting front depth, which is effectively the depth of failure (or zone of reduced soil suctions) in a planar failure mode shown in Figure 42. Typically wetting front depths or failure zones below 0.5 m, are of no consequence to operation and safety of the network. The depth of developed wetting

[27] Kenneth Gavin and Jianfeng Xue; (2009) 'Use of a Genetic Algorithm to perform Reliability Analysis of unsaturated soil slopes'. Geotechnique, 59 (6):545-549. [DOI] [Details]

front and the suctions in a slope depend both on the rainfall intensity of the storm which causes a failure to develop, and of course the initial conditions in the slope at the start of this rainfall event. The latter is controlled by the antecedent rainfall. Usually an interaction diagram is used, which considers the antecedent rainfall over the previous 5-day period and the 1-day rainfall intensity which triggers the failure. Whilst the actual threshold values are likely to site and soil specific, these two parameters provide a useful reference point for the RAIN project.

The following images, Figure 43 and Figure 44, represent the relationship between the rainfall and landslip occurrence for England and Wales and for Scotland. It can be seen that there are two peaks, one during the summer and one in high winter, both related to periods with increased precipitation.

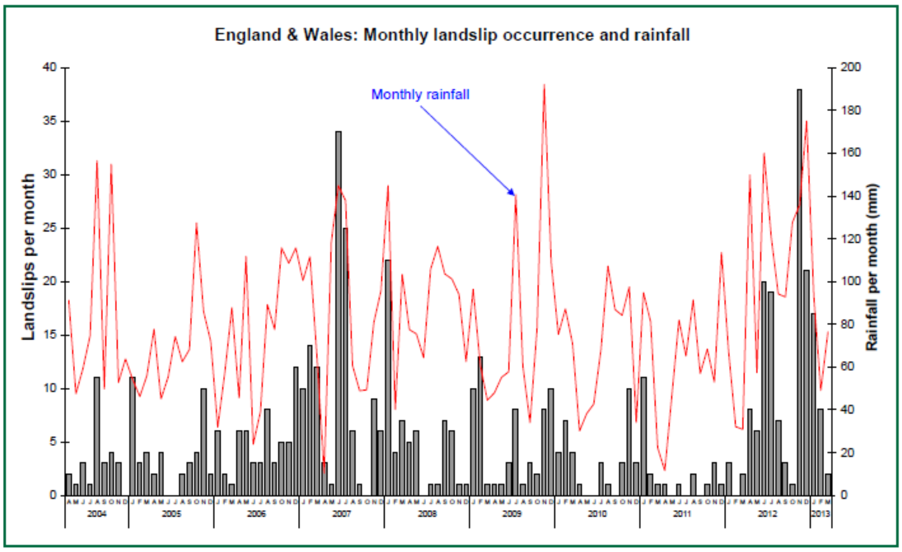


Figure 43 Rainfall and earthwork events on Network Rail infrastructure in England and Wales [23]

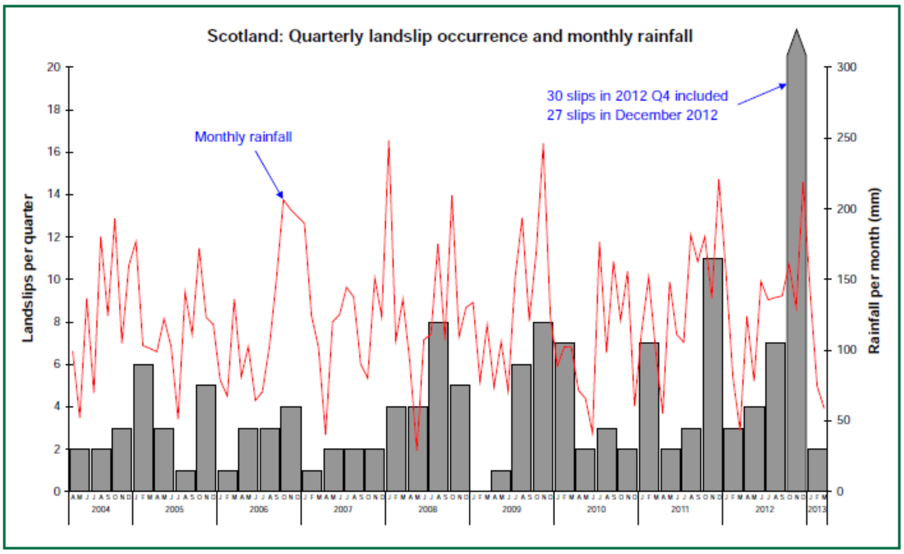


Figure 44 Rainfall and earthwork events on Network Rail infrastructure in Scotland [23]

3.3.4 Remediation measures which increase resilience

Since landslides result from complex interactions between geological and triggering factors of different origins (EEA 2010), many of the factors cannot be controlled or influenced. However, many factors such as land cover or slope angle can be varied to either increase the resistance of a given slope or mitigate the impacts of a failure if it occurs. Methods that fit both of these scenarios are discussed in this report. Where no direct remediation is planned, monitoring and alert networks, prioritisation of interventions and relocation of the network can be undertaken. These are not considered in detail herein.

3.3.4.1 Methods to increase resistance

Drainage: Surface drainage techniques commonly adopted for transport infrastructure networks include lined and unlined open ditches, buried drains such as herringbone drains, Figure 45. The latter are relatively cheap to install and are relatively effective at controlling suctions at depth of up to 1.5 m particularly in more temperate climates.

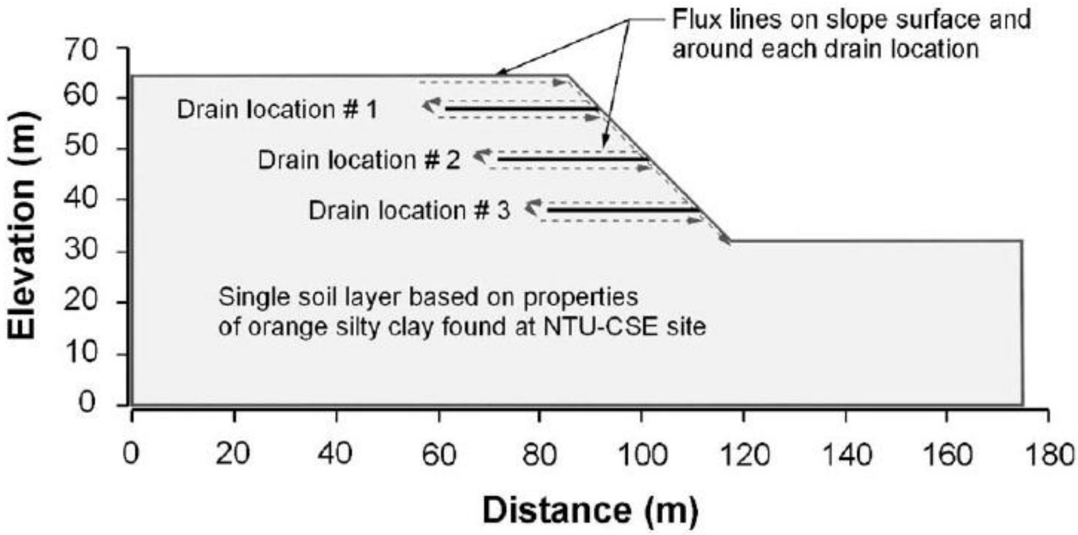
Figure 45 (a) Herringbone drainage system in rail cutting [28] (b) Surface drainage culvert on an Irish Rail cutting [29]

In tropical climates where rainfall intensities can lead to the development of deep wetting fronts (in the order of several metres), horizontal drainage of the form shown in

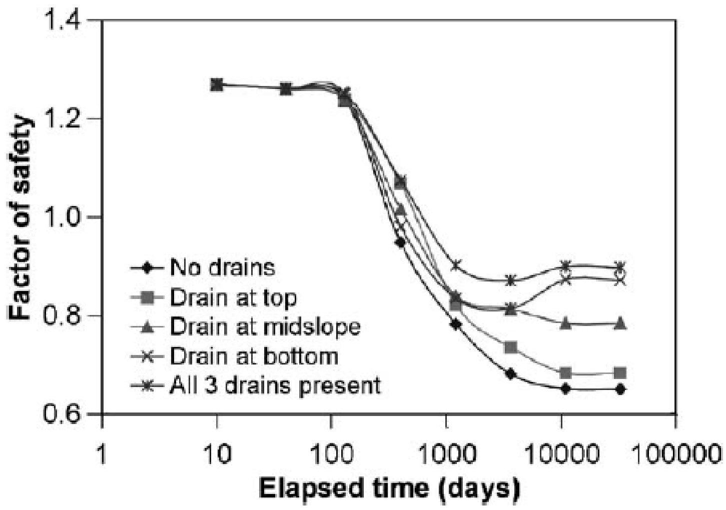
Figure 46a can be adopted to control deep water tables. Rahardjo et al. (2003) performed field tests at two sites and a parametric numerical analysis to investigate the effectiveness of horizontal drains during intense rainfall in the deeply weathered tropical soils of Singapore. The field tests suggested that horizontal drains were relatively ineffective at controlling pore pressures in near surface soils (within 1.4 m of the slope surface), with sections of the slope with and without drainage having similar pore pressure profiles. At deeper depths the suction values were higher where drains were present. Numerical analyses were performed using the GeoSlope software package to assess infiltration and stability. The analyses considered three drain locations, shown in

28 http://www.cml-civil-engineering.co.uk/clay-cross.html
29 Irish Rail Archive

Figure 46a. The drain (location 3) at the bottom of the slope was by far the most effective location. In contrast the drain (location 1) near the slope crest was relatively ineffective.



(a)



(b)

Figure 46 Numerical analyses performed using Geoslope, (a) numerical model used in the analysis showing drain locations, (b) Results for various drain layouts[30]

[30] Rahardjo et al. 2003

Vegetation: Greenwood et al. (2004) describe the use of vegetation to increase the stability of soil slopes. The trees provide a natural suction stress which lowers the phreatic surface and maintains negative pore pressures in the slope,

Figure 46.

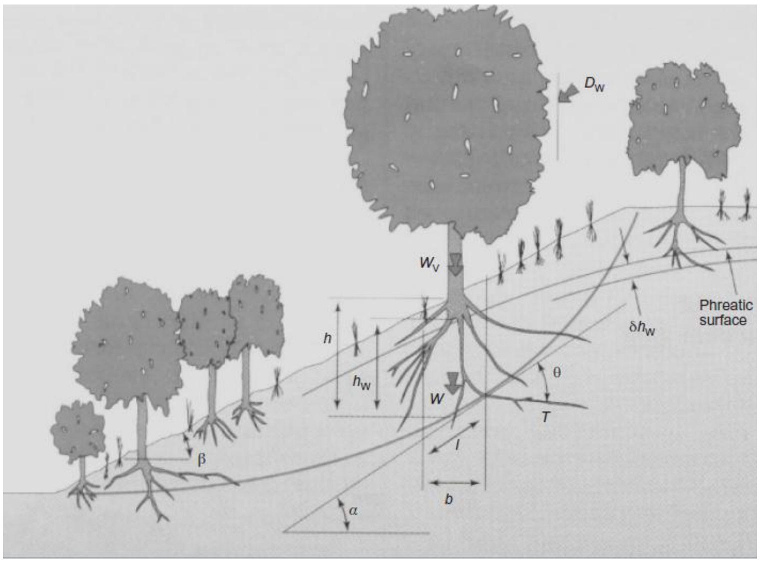


Figure 47 The influences of vegetation on slope stability [31]

On steep engineered slopes the development of vegetation can be aided by the introduction of geocell mattresses, Figure 48. These allow the establishment of vegetation on steep slopes and inhospitable conditions. In addition to providing added stability they improve the aesthetic condition.

Figure 48 (a) Engineered slope (b) Stabilisation of natural slope

[31] Greenwood et al. 2004

[32]

Measures which can be taken to increase the resistance of the slope or reduce the disturbing force include, slope re-grading, soil improvement and structural inclusions (piling and soil nailing). One of the cheapest methods of increasing the factor of safety of an existing slope is to reduce the slope angle by re-grading, Figure 49. Whilst this can substantially reduce the disturbing force, the additional footprint required often precludes the adoption of this measure on existing networks.

Figure 49 Slope regrading [33]

Where space constraints dictate, the provision of gabion baskets, Figure 49, can effectively allow for re-grading of the upper slope, whilst maintaining the existing slope footprint.

Figure 50 Irish Rail Embankment remediation [34]

In the case of new construction, addition of extra lanes/track, repair of a slips or major reconstruction works, the use of geogrid reinforcement (Figure 51) can prove to be an effective solution where space is a constraint. The geogrids which have high tensile resistance, mobilise interface friction forces with the selected fill to prevent pull-out.

[32] http://www.prestogeo.com/slope_protection
[33] http://www.cml-civil-engineering.co.uk/clay-cross.html
[34] Irish Rail Archive??

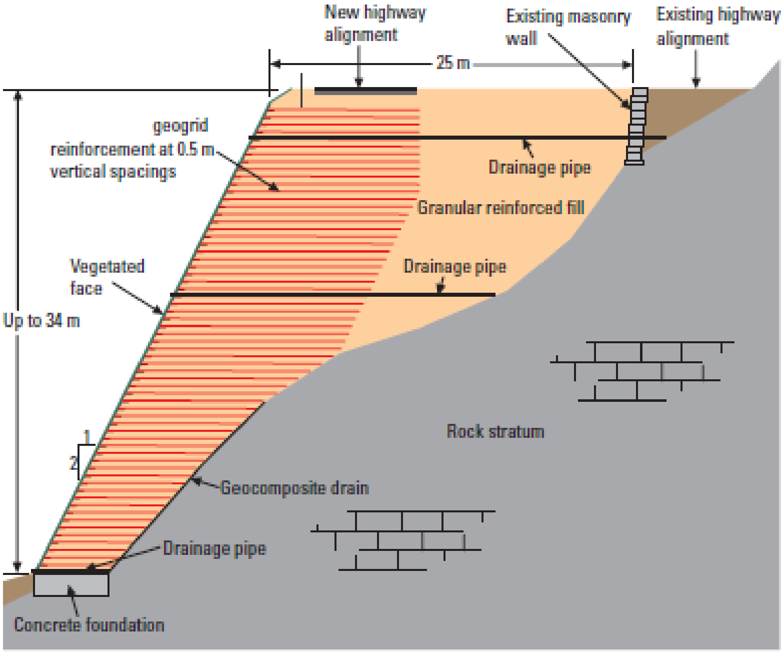


Figure 51 Goegrid reinforcement [31][35]

Structural solutions in the form of piles and soil nails tend to be expensive, however, they are an effective way of upgrading existing slopes where space constraints might preclude other solutions. The piles work by providing additional lateral shear resistance by intersecting potential failure surfaces (Figure 52), whilst soil nails are essentially tension members (high strength steel bars encased in grout) which are drilled far beyond the potential failure surface and provide additional anchor forces to prevent failure. Some form of load transfer mechanism on the slope surface is required with the anchor system; Figure 53a. Anchoring solutions are particularly effective for stabilising fractured rock slopes, Figure 53b.

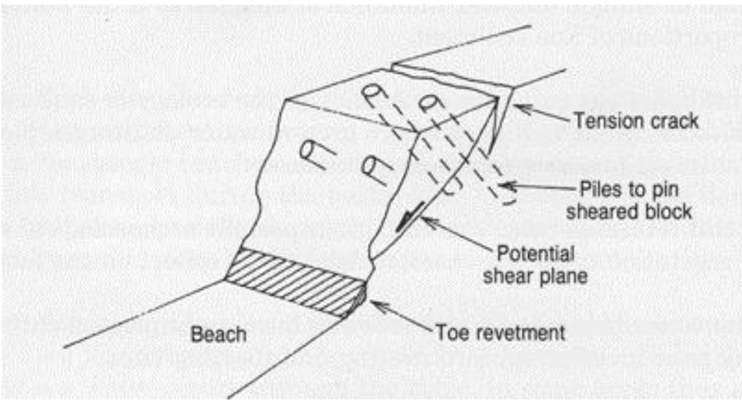
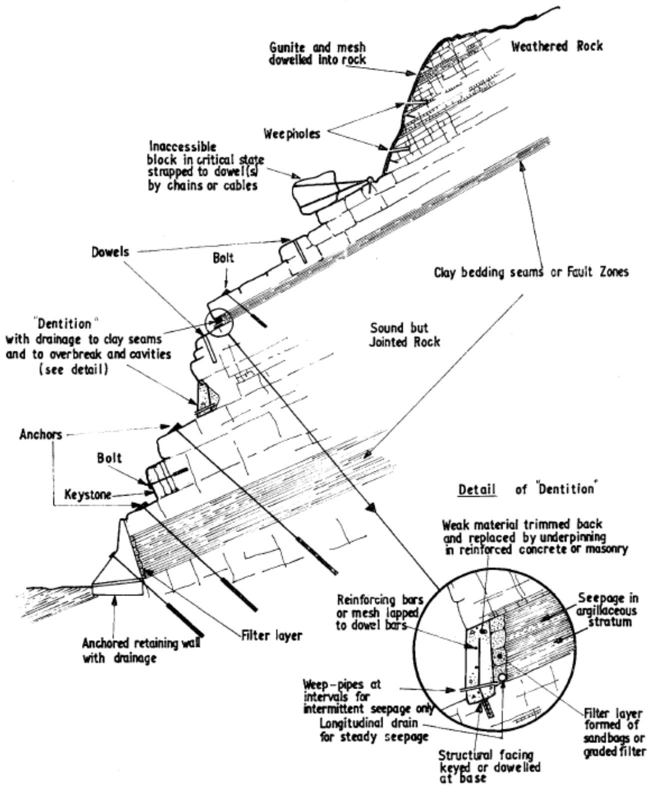


Figure 52 Use of piles to stabilise embankment [36]

[35] http://www.tencate.com/

(a)



(b)

Figure 53 Soil Nails (a) Soil slopes [37](b) Rock Slopes [38]

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[36] http://www.southwestcoastalgroup.org/cc_defence_cliffstrengthening.html
[37] http://www.haywardbaker.com/
[38] ???

3.3.5 Mitigation measures which decrease impact of failures

Saturated soil in steep slopes is prone to shallow landslides and can develop speed up to 10 m/s (Geobrugg). Conventional protective measures usually imply construction of structures which have primary role in diverting the landslide (such as reinforced walls and dams). This requires a certain amount of time for the design and even longer to construct. Flexible shallow landslide barriers, Figure 54, are able to retain mixtures of water and soil, and require much less time to construct. Also, in order to construct a structure by conventional methods very often certain portion of soil is excavated to facilitate the new structure-this can lead to further degradation of slopes natural stability.

Figure 54 Shallow landslide barrier [39]

Shallow landslide barriers consist of posts which facilitate and guide spiral rope nets and protective mesh apron (which serves as an erosion seal between the ground and the barrier). Spiral rope nets are anchored into the ground by spiral rope anchors and brake rings are incorporated in the support and the retaining ropes. Once the major event happens the breaks are activated thus enabling the net and the ropes to safely lock-in the soil.

3.3.5.1 Rockfall nets

Rockfall nets act on a similar principal to shallow landslide barriers. The difference is in the catchment net, which is constructed according to rock impact and is usually made of interlocked rings, Figure 55.

[39] http://www.geobrugg.com/en/home-en

Figure 55 Rockfall net [39]

3.3.5.2 Rockfall drapes

Drapes are used to mitigate the impact of rock sliding on rock slopes and to secure the loose rock even on irregular surfaces. The main difference between the classic net and the drape is in the flexibility. Drapes wrap around irregular surfaces, Figure 56a, and offer more coverage with the rock interface. Some of the drapes have an incorporated erosion control mat which allows both dry and wet seeding, Figure 56b.

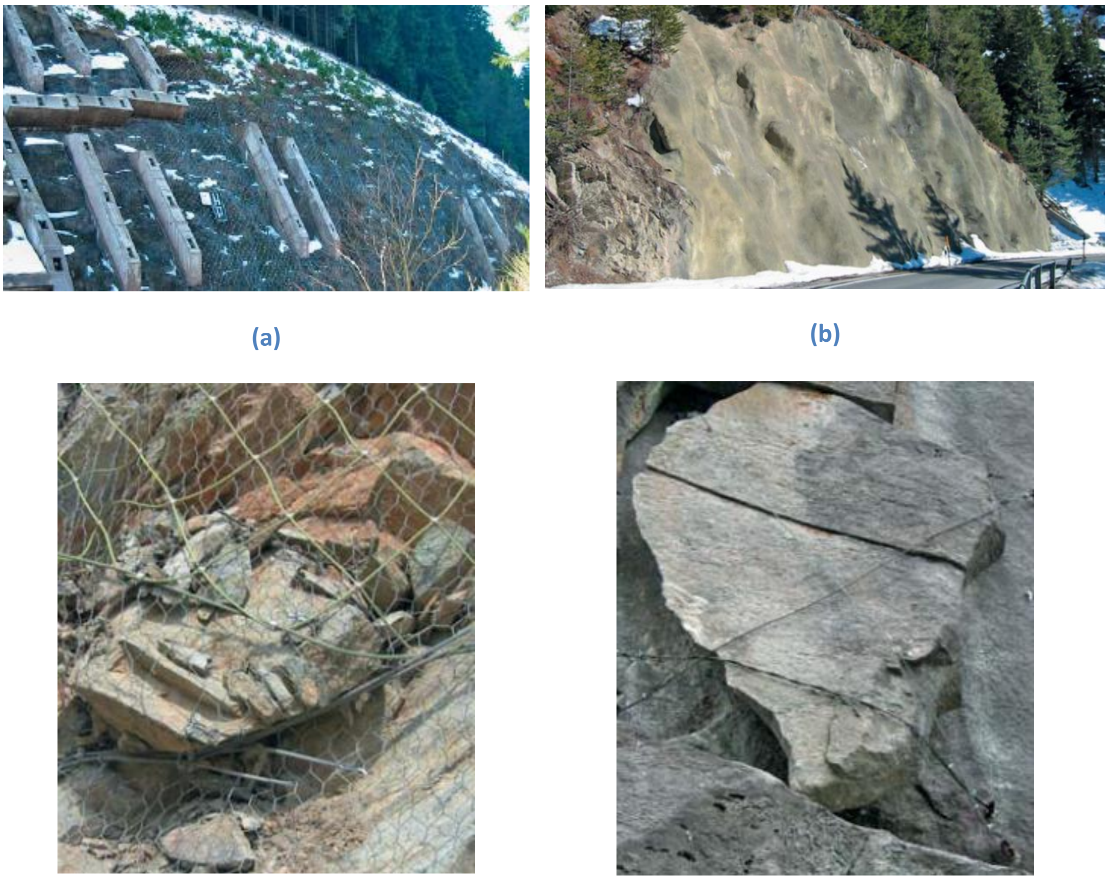
(a) (b)

Figure 56 (a) Wire drape rapped around irregular surface, (b) Wire drape with seeding [39]

3.3.5.3 Other rockfall prevention methods

Alternative methods for preventing rock falls are shown in ***Figure 57***. Protection provided by anchored beams, **Figure *57***a, usually requires difficult and cost intensive construction, with road closures during construction. An example of a sprayed concrete cover (e.g. shotcrete) is shown in Figure 57b. When used with anchors and mesh the resulting increased capacity of the slope can lead to a larger factor of safety against failure however, the aesthetics are of concern. Particular attention to the drainage system is required as these often get clogged at an early stage, which can lead to water pressure building up and fine material washing out behind the shotcrete layer, thus leading to sudden failure of the protective cover and possible collapse of the structure.

Wire rope nets, Figure 57c, are often used alongside rock nails and anchors to provide a flexible method for securing rock. The geometry of the net allows only for minor zinc plates which leads to corrosion of the fastening elements and offer limited amount of strength. Additionally individual net panels can only cover several square metres. Wire rope restrains, Figure 57d, have proven to have only a limited effect, since the stabilisation is not offered in all directions. The ropes can only work locally and are difficult to adjust to irregular surfaces. Also, with time the tension in rope reduces hence the protection level is compromised.



(a) (b)

(c) (d)

Figure 57 Anchor beams (a), Shortcrete cover (b), Wire rope nets (c), Wire rope retrains (d) [39]

3.3.5.4 Monitoring and mapping

Although monitoring and hazard/inventory mapping cannot be classified as a physical measure to provide resilience to a slope, they have an important overall role, when it comes to management, safety, planning and execution of physical works. A good example is Norway's landslide and avalanche alert system which is run by Directorate of Water and Energy Resources (NVE). The established services give out warnings of avalanche and landslide danger at a regional level, with an aim of reducing numbers of accidents, casualties and general damage. Another good example is the Swiss Federal Institute for Forest, Snow and Landscape Research, WSL which provides maps of damage processes such as Floods, Debris flows, Landslides (as presented in Figure 58) and rockfalls on an annual scale.

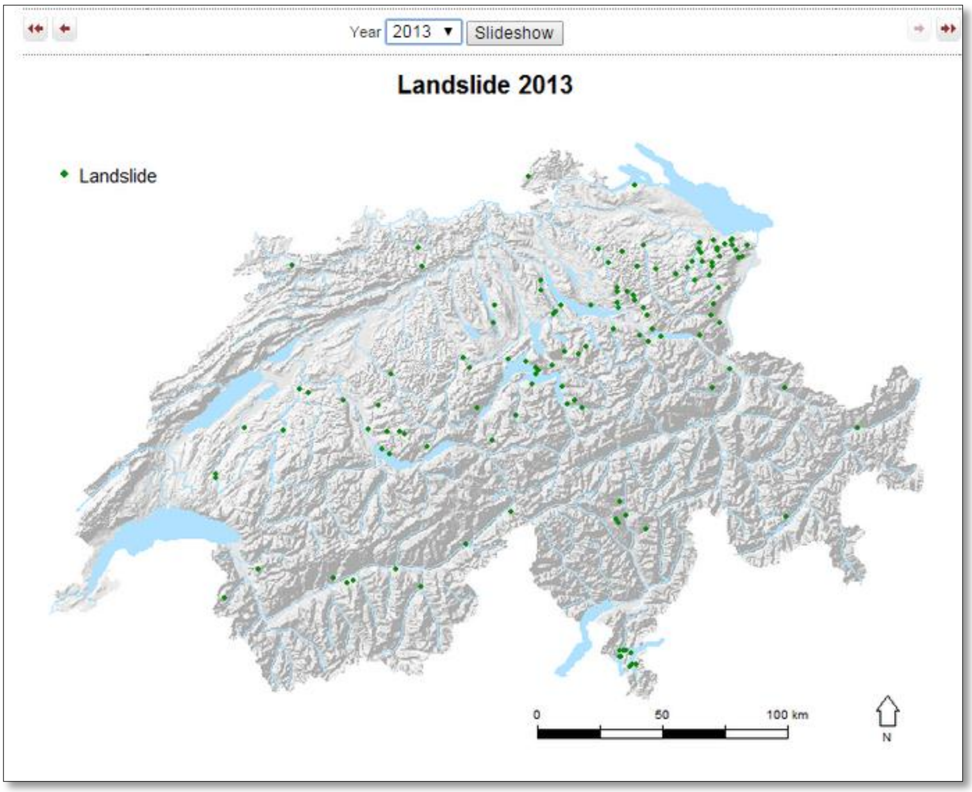


Figure 58 Inventory Landslide Mapping for 2013 [40]

[40] http://www.wsl.ch/index_EN

3.4 Rail track including switches and crossings

3.4.1 Definition

Railway is a guided way, meaning that the tracks determine the path which the train will take, therefore the tracks and crossings and switches (referred to as C&S herein) are considered as crucial elements. The major components of the railway track system are shown in the Figure 59 below, and are tracks (including switches and crossings), sleepers, ballast and substructure (subgrade).

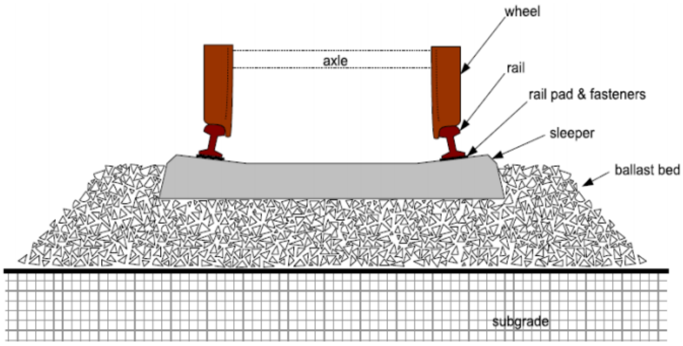


Figure 59 Railway track system and the components [41]

Turnouts, or switches and crossings, are the devices which are used in order to divide single track into multiple tracks, providing movement in a straight or divergent direction, intercepting at the same level.

C&S are the devices which allow trains to:

- Chose the tracks to continue their way in different directions,
- To join multiple tracks or to split up a single track,
- To change track or to continue their way in the same direction but on a different track,
- To cross other tracks.

The different types of crossings are illustrated in Figure 60 (source infoscience ch.)

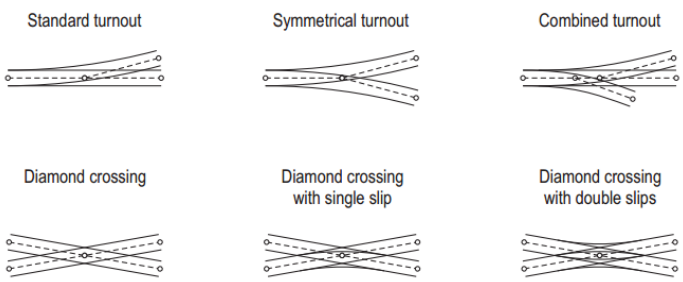


Figure 60 Categorisation of C&S types by their function [42]

[41] Hassankiadeh, S.J. (2011): Failure Analyisis of Railway Switches and Crossings for the purpose of Preventive Maintetnance

The components of Switches and Crossings, Figure 61 are as follows:

- SWITCH BLADES and accompanying STOCK rail, including the SLIDING CHAIRS
- The FROG
- The CHECK RAIL with the CROSS-Bar
- The COMMON CROSSING (only for diamond crossings and diamond crossings with single and double slips)
- The INTRMEDIATE RAILS
- The SLEEPERS
- The BALLAST
- The SUBSTRUCTURE (SUBGRADE)

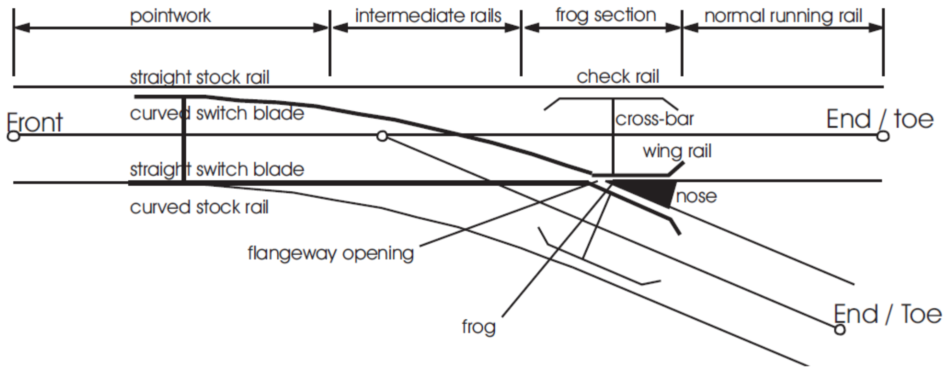


Figure 61 Standard Right Hand Turnout [39]

The failures which can occur in the tracks can be classified either based on the component's failure or on the nature of the failure;

- *Failure classification based on the component's failure:*
  -rail failure
  -sleeper failure
  -ballast failure
  -subgrade failure

- *Failure classification based on the nature of the failure:*
  -fatigue cracks failure
  -rolling contact fatigue cracks
  -wear failure
  -material deformation failure
  -shear failure

[42] *Zwanenburg, W.J.* (2009): Modelling Degradation Processes of Switches and Crossings for Maintenance & Renewal Planning on the Swiss Railway Network

Although the failures mentioned above are caused by “wear and tear”, the focus of this deliverable is put on the severe weather hazards and their impact to the tracks and C&S.

3.4.2 Examples of Failures

3.4.2.1 Lichfield Midlands

BBC News UK reported a freight train accident in which the train derailed off tracks near Lichfield in the Midlands in the summer of 2008. Fortunately there were no casualties, but the crash closed the West Coast Main Land. The track had buckled in the sun, causing the train to come off tracks and crash. **Figure 62** shows an example of tracks buckling in the heat.

Figure 62 An example of rail tracks buckling [43]

3.4.2.2 Bretungny-sur-Orge

According to RFI (Radio France Interantionale) poor Maintenance was found as a cause for the Train crash in July 2013 in Bretugny-sur-Orge near Paris, Figure 63, which left seven people dead and a 61 people injured. The intercity train had just left Paris and was heading towards Limoges when it derailed, crashing into a station platform, Figure 64. A total of 385 passengers were on board when the train crashed and the station platforms were crowded at the start of a holiday weekend. It is one of the deadliest train accidents in France for 25 years. A 10 kg steel clip (splice bar), was the major cause of the derailment. The clip was supposed to be bolted to the track, at the switch point, but instead it was detached and blocked the track. The experts ruled out the accident as a “malicious act”, but found more than 200 irregularities in the surveyed section of the rail track. Most of the track effects were known to the SNCF (Société nationale des chemins de fer français=National society of French railways) but they were not amended adequately and the main cause was

[43] http://www.powelectrics.co.uk/level-monitoring/application.asp?page=remote_temperature_monitoring_281

attributed to a lack of maintenance. After the accident, the SNCF launched a massive security check of more than 5000 steel clips all over the French rail network.

Figure 63 Accident in Bretugny-sur-Orange [44]

Although this accident was not caused by a severe weather event it is an example how lack of maintenance and monitoring have a severe impact on operation and safety.

Figure 64 Train crashed into the station platform [45]

[44] http://www.lejdd.fr/Societe/Actualite/Bretigny-une-catastrophe-qui-appelle-des-reponses-619101

3.4.2.3 Dawlish Storm

In February 2014 Dawlish was hit by a storm surge, Figure 65, and the railway line connecting Devon and Cornwall to the rest of the UK was severely damaged, Figure 66. Around 200 homes were left without power. More than 150 properties were evacuated during the 90mph storm.

Figure 65 Dawlish Rail Line under the Surge Impact [46]

Network Rail has assessed the cost of the track damage at up to £14 million for the repair of the 80 m section. The Met office stated that this is one of the exceptional periods of rainfall in the last 248 years. Records for Wales and England dating back to 1870s show that winter 2013/2014 was the wettest on record.

Figure 66 Damaged Dawlish Rail Line [47]

[45] http://www.bbc.com/news/world-europe-23298374
[46] http://dawlishairshow.co.uk/newindex/dawlish-storm-update/

[47] http://www.bbc.com/news/uk-england-26062712

In November 2014 another storm with wind gusts of 93 mph was recorded at Berry Head in Devon around noon and the Met Office issued an amber wind warning. Coping stones were reported being knocked loose on the Dawlish railway line, in the exact sea wall that was repaired earlier that year.

3.4.3 Potential Impacts

The parameters which cause deterioration and degradation in tracks and C&S are mostly related to train loads (cargo/passenger train) and train frequency, or whether the real speed exceeds the design speed limit. Although most of the cracks and deformations in the rail tracks originate from poor manufacturing, improper construction, accompanied by the applied cyclic (fatigue) or excessive load, extreme weather effects also contribute to degradation or deterioration of the tracks.

According to EC report "Adapting infrastructure to climate change" the following Table 4 summarises the climate change effects which have an impact on the railway infrastructure:

Table 4 Climate Change effects on Railway infrastructure

Climatic Pressure	Risk	Time Frame of expected Impact	Regions mainly affected
Summer heat	• Rail buckling • Increased Material fatigue • Overheating of equipment • Increased risk of wildfire	Medium negative (2050-2080) to high negative (2080)	Southern Europe medium negative until 2025 and high negative until 2080 West, East and Central EU medium negative until 2080
Winter cold/ice	• Ice on trains and catenary	Medium negative (2025-2080)	Northern Europe, Central Europe
Extreme precipitation	• Damage on infrastructure due to flooding and/or landslides • Scour to structures • Destabilisation of embankment	Medium negative (2025) to high negative high negative (2080)	European Wide

In general	• Reduced safety • Increased coast for reparation and maintenance • Disruption of "just in time" delivery of goods and passengers

In addition to direct weather impacts on the rail tracks, climate impacts can also be indirect, causing additional stresses and contributing to deterioration of these elements. In addition many IM's suffer financial penalties when infrastructure is unavailable. Switch rails and the ballast are considered to be mostly affected elements. Also sleepers, either concrete or wooden, are subject to climatic impacts. Increased precipitation (flood) or drought on the other hand will both lead to degradation in an organic material such as wood, but also trigger a different degradation mechanism in the concrete sleepers. Because the tracks lay on the sleepers, they are indirectly subject to negative impacts which affect the sleepers and the subsoil, e.g. during a flood, the ballast can be washed out causing the rail track to collapse. Ground frost has also a direct impact on the ballast. The freeze-thaw phenomenon is associated with ground frost and relates to the thawing of ground ice. The ground ice starts to thaw when the frost ceases to increase, and generally starts from the top layer of the frost, where unthawed ice layer prevents the thaw water from flowing downwards. The softening soil layer is usually of a fine grained soil type, such as clays and silts. Rain and thaw waters import fine-grained soil from the uppermost gravel layer to the unfrozen layer. As the train travels over the sleepers, the generated stress cannot be released through the frost layer, the excess pore pressure build up leads to a loss of strength and stiffness. Figure 67 shows the freezing rain in Slovenia at the end of January 2014, where this effects caused a line closure.

Figure 67 Freezing Rain in Slovenia 2014 stops the railway traffic [48]

Figure 68 presents the number of failure modes for the UK railway data for 2009. It indicates that there is a relationship between the seasons and the failure of components. Rainy autumns (accompanied by stockpiling of fallen leaves) and cold winters (ice and snow) have the biggest impact on the rail track system.

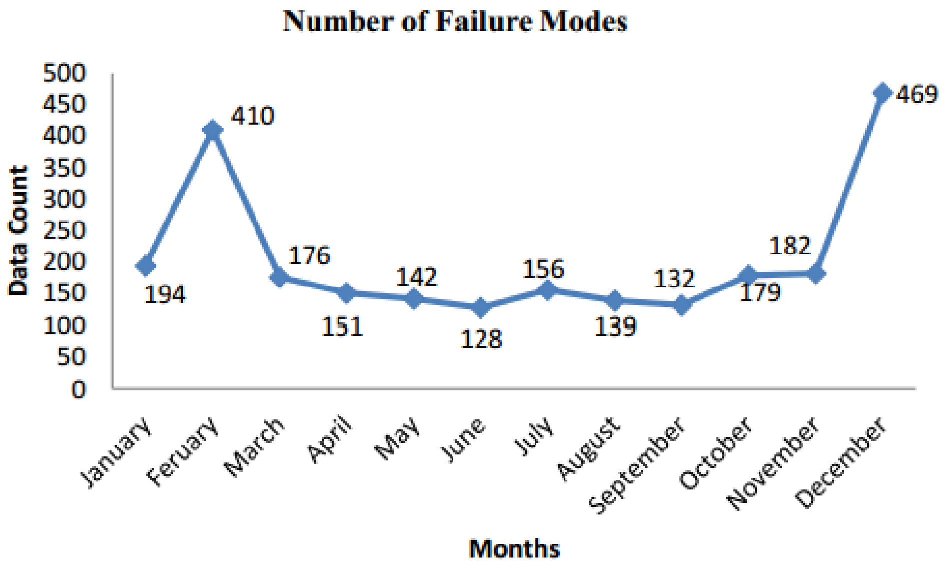


Figure 68 Number of Failure modes for the UK railway data 2009 [41]

[48] http://blogandoaqui.blogspot.ie/2014/12/25-astonishing-landscapes-caused-by.html

3.4.4 Remediation measures which increase resilience

Remediation can be provided either by alternative design, monitoring and/or maintenance.

The main technique used to prevent rail buckling is the use of pre-stressing or stretching. When the temperature rises the metal cannot expand any further. By doing this the tracks can withstand the temperatures up to 30 ^{o}C.

Network rail in the UK recommend some of the following remediation strategies in regards to train buckling:

- If the track comprises short rails bolted together, small gaps should be left between each length to allow for some expansion;
- Most track is made up of long stretches of rail that are stretched and welded together, resulting in reduced compression - and a much lower risk of buckling - when they heat up;
- The stability of the track is checked each winter and weaknesses detected should be strengthened before the summer arrives; typically this includes replenishing the ballast that surrounds the sleepers, and re-tensing continuously welded rails;
- Work that will disturb the stability of the track is avoided during the summer as this increases the chance of a track buckle, though sometimes it cannot be avoided;
- At-risk rails are painted white so they absorb less heat, reducing rail temperatures. Typically a painted rail will be five to ten degrees cooler than an unpainted rail;
- Measures are continually enhanced for calculating rail temperatures, including installing probes that give us instant alerts when track temperatures rise;
- On very hot days when high rail temperatures are widespread, speed restrictions are imposed at vulnerable locations; slower trains exert lower forces on the track, reducing the risk of buckling.

It is important to note that when the track is pre-stressed before installation it cannot stretch any further, but if it is stretched too much it will then crack at lower temperatures, this can cause problems in many climates. Remote distancetemperature monitoring systems are available on the market. Telemetry helps measuring the temperature of the track, telling indicating whether the track is in the direct sunlight or not and the type, speed and frequency of trains with this information the managers can decide to make appropriate decisions on time.

In order to prevent buckling, some of the countries use a system where the track is laid on reinforced concrete slabs, rather than on sleepers and ballast. This system is called "slab track". The installation cost for this system is typically up to four times more costly than standard systems.

Although there are benefits in term so saving on maintenance costs, it is hard to advocate this choice from the financial point of view. Although, most of the measures which rail owners/managers implement are directly to the treatment of the tracks and C&S, some countries put an emphasis on hazard management as a preventive measure to the possible natural hazard impact on the railway infrastructure. A good example is OBB (Osterreichische Bundesbahnen) who have been investing in Natural Hazard Management over the last several years, and according to their investigation Austria is affected by the following natural hazards presented in Figure 69.

Natural Hazard	predictable	influenceable
Earthquake	🔴	🔴
Rockfall	🔴	🟢
Slide	🔴	🟢
Continuous rainfall	🟢	🟢
Thunderstorm	🔴	🔴
Torrential process	🟢	🟢
Flood	🟢	🟢
Avalanche	🟢	🟢
Gale	🟢	🟢
Forest fire	🟢	🔴

Figure 69 Natural Hazards which affect Austrian Railways [49]

The main philosophy in the OBB approach is to rather work on prevention, concentrating on risk reduction as presented in the Figure 70, by forming natural hazard maps, incorporating weather information system and provide technical training, etc. OBB's Avalanche Commissions have proven to be very effective and the principal will be applied to the similar weather related hazards.

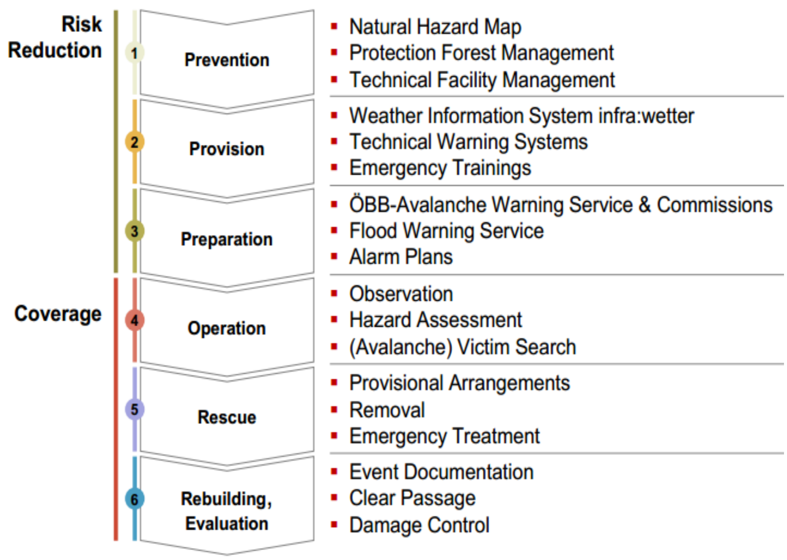


Figure 70 OBB's approach [49]

[49] http://www.mowe-it.eu/wordpress/wp-content/uploads/2013/07/Natural-Hazard-Management_17092013.pdf

3.5 Tunnels

3.5.1 Definition

Tunnels have become important infrastructures for modern transport networks. They can be considered as an individual component of the road network, such as bridges and road sections. In addition underground excavations have facilitated development in urban areas below ground level, including all types of buildings and public or private facilities, thus improving the use of public space. AS a result of technological advances, tunnels have been continuously growing in size and implementing new construction machinery and methods, to the point that some of these infrastructures result in very large dimensions, such as:

- The “Laerdal” tunnel, in Norway, with 24.5 kilometres length;
- The “Zhongnanshan” tunnel, in China, with 18.2 kilometres length and 6 metres high;
- The “San Gotardo” tunnel, in Switzerland, with 17 kilometres length and 17000 vehicles/day. A new second parallel tunnel is expected to be built in 2027

(a)

(b)

(c)

Figure 71 (a) Laerdal Tunnel [50](b) Zhongnanshan [51]and (c) San Gotardo Tunnel [52]

Table 5 provides a summary of different types of tunnels in regards to material typology, construction method, different types of use etc.

[50] http://i137.photobucket.com/albums/q209/harsh42/Viking%20Tour%202010/_DSC6245.jpg
[51] http://degiorgi.math.hr/~vsego/phun/zhongnanshan_tunnel/
[52] http://blog.360gradosenconcreto.com/san-gotardo-el-tunel-ferroviario-mas-largo-del-mundo/

Table 5 Tunnel Classification Summary Table

<table>
<tr><th colspan="7">TUNNEL CLASSIFICATION</th></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="6">1.1.1</td><td rowspan="6">Typology or construction method</td><td rowspan="6">1.1.1.1</td><td rowspan="6">Excavation tunnels</td><td></td><td>With a tunnel-boring machine</td><td rowspan="3"></td></tr>
<tr><td></td><td>Mechanical excavation</td></tr>
<tr><td></td><td>Drill and blast</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Cut and cover tunnels</td><td>Bottom up</td></tr>
<tr><td>Top down</td></tr>
<tr><td></td><td>Immersed tunnels</td><td></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="2">1.1.2</td><td rowspan="2">According to ground material typology</td><td>1.1.2.1</td><td>Rock tunnels</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>1.1.2.2</td><td>Soft ground tunnels</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="5">1.1.3</td><td rowspan="5">According to different loads and uses</td><td>1.1.3.1</td><td>Pressurized tunnels</td><td colspan="3">Hydraulic tunnels, gas storage tunnels</td></tr>
<tr><td rowspan="4">1.1.3.2</td><td rowspan="4">Unpressurized tunnels</td><td></td><td>Hydraulic tunnels</td><td rowspan="4"></td></tr>
<tr><td></td><td>Railway tunnels</td></tr>
<tr><td></td><td>Road tunnels</td></tr>
<tr><td></td><td>Pedestrian tunnels</td></tr>
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<tr><td rowspan="2">1.1.4</td><td rowspan="2">According to cross section typology</td><td>1.1.4.1</td><td>Circular section tunnel</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>1.1.4.2</td><td>Horseshoe section tunnel</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="2">1.1.5</td><td rowspan="2">According to relative situation</td><td>1.1.5.1</td><td>Singular tunnel</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>1.1.5.2</td><td>Twin tunnels</td></tr>
</table>

Most of the failures in the tunnels are related to the type of ground surrounding the tunnel i.e. rock or soft ground (gravel, sand and clay). These will be discussed in subsequent sections but the major concern regarding the impact of weather hazards for tunnels is flooding.

However, understanding the failure mechanism of a rock mass surrounding an underground opening is essential in the design of support systems for the openings. The failure mechanism depends on the in situ stress level and characteristics of the given rock mass. At shallow depths, where the rock mass is blocky and jointed, the stability problems are generally associated with gravity falls of wedges from the roof and sidewalls since the rock confinement is generally low. As the depth below the ground surface increases, the rock stress increases and may reach a level at which the failure of the rock mass is induced. This rock mass failure can include spalling, slabbing, and major rock burst. Some of the possible rock failure mechanisms include: wedge failure, stress induced failure, squeezing and swelling. As discussed before, rock is a strong material which requires little or no structural support when intact. However, when the rock joints and fractures are open enough so that the natural rugosity (measure of small-scale variations or amplitude in the height of a surface) of the block surfaces will not prevent movement of rock blocks or substantial fragments, the rock is said to be "blocky." If the joints and fractures contain clay-like material resulting from weathering or light shearing, then the rock is described as "blocky and seamy." This may raise the rock load by a factor of approximately three. In zones where the rock has small folds, but is open along the direction of the folds, it may be free to move in only one direction. Such rock is still blocky.

In non-cohesive Sand and Gravel the usual problem encountered is related to running sand settlement and cratering at the surface with damage to structures or utilities in the area. If the ground is permeable, a tunnel boring machine, e. g. slurry shield type or Earth Pressure Balance (E.P.B) shield techniques should be used. If dewatering is successful in depressing the water layer below the tunnel invert, it may be found that dry sand is just as unstable as wet sand. The alternative of using compressed air is attractive, provided the working pressure is very carefully controlled; but even so, the ground may be too dried out for stability.

For the purposes of this discussion, soft clay will include any plastic material that will close around a tunnel excavation if free to do so. This will be the case if the overburden pressure at spring line (ridge of permeable over impermeable rock) exceeds the shear strength of the clay by a factor of about three or more. However, if the clay is sensitive and loses strength when remoulded, the remoulded strength will govern some of the clay behaviour during tunnel construction.

The two most common methods used in tunnel construction are the (a) New Austrian Tunnel Method (NATM), Figure 72, and (b), the Tunnel Boring Machine (TBM),Figure 72. . In NATM the tunnel is sequentially excavated and supported, with the initial ground support provided mostly by anchors and shotcrete. Permanent support typically consists of a cast-in-place concrete lining with a waterproof membrane. In contrast, TBM progresses through the ground with a cutter head, followed by a main bearing, thrust mechanism and trailing support mechanism (back-up system in the finished part of the tunnel, containing slurry pipelines, control room, electrical system, ventilation, mechanism for transport of pre-cast tunnel lining segments etc.).

(a) (b)

Figure 72 Rock Tunnel (a), Soft Ground Tunnel (b) [53]

3.5.2 Examples of Tunnel Failures

3.5.2.1 Penmanshiel Tunnel (Scotland)

The Penmanshiel Tunnel is a now-disused railway tunnel near Grantshouse, Berwickshire, in the Scottish Borders region of Scotland, Figure 73. It was formerly part of the East Coast Main Line between Berwick-upon-Tweed and Dunbar.

The tunnel was constructed during 1845-46 by the contractors Ross and Mitchell, to a design by John Miller, who was the Engineer to the North British Railway. Upon completion, the tunnel was inspected by the Inspector-General of Railways, Major-General Charles Pasley, on behalf of the Board of Trade.

The tunnel consisted of a single bore, 244 metres long, containing two track lines. During its 134-year existence, the tunnel was the location of two incidents investigated by HM Railway Inspectorate, and serious flooding. The first was in 1949, when a serious fire destroyed two carriages of a south-bound express from Edinburgh. Seven passengers were injured, but there were no fatalities.

On the day of 12th of August 1948, 160 mm of rain fell in the area. The total rainfall for the week was 265 mm. Rain falling on the Lammermuir Hills surged into the Eye Water towards Reston and the channel could not accommodate all of the water. The flood water then backed up the tunnel and flowed to sea in the opposite direction, towards Cockburnspath. The tunnel was flooded to within 70 cm of the crown of the portal. The damage caused by these floods led to the temporary closure?? of much of the railway network in the south east of Scotland.

The second incident occurred on the 17th of March 1979 when, during improvement works, a length of the tunnel collapsed. Two workers were killed, and 13 others managed to escape. The tunnel was sealed up and a new alignment was made for the railway, in a cutting to the west of the hill.

[53] http://www.wired.com/2012/08/21st-century-tunnel-earthquake/

Figure 73 Penmanshiel Tunnel Scotland [54]

3.5.2.2 Brooklyn Battery Tunnel, Hurricane Sandy (New York)

Hurricane Sandy was a Category 3 (178–208 km/h) on Saffir–Simpson hurricane wind scale (SSHWS) storm at its peak intensity when it made landfall in Cuba. While it was a Category 2 storm off the coast of the North-eastern United States, the storm became one of the largest Atlantic hurricanes. In the United States, Hurricane Sandy affected 24 states, including the entire eastern seaboard from Florida to Maine and west across the Appalachian Mountains to Michigan and Wisconsin, with particularly severe damage in New Jersey and New York.

The resulting storm surge hit New York City on October 29th, 2012, flooding streets, tunnels and subway lines and cutting power in and around the city. Flooding occurred across the entire city; Peter Cooper Village, 22nd and 27th Street, Tribeca, the Upper West Side, Upper East Side, the banks at Brooklyn, then the airports Kennedy and La Guardia. The Brooklyn Battery Tunnel, Figure, was flooded too (it is the main traffic route between Manhattan and Brooklyn). Seven more subway tunnels under the East River were flooded.

Figure 74 and Figure 75 show road and subway flooding in New York City Area.

[54] https://c1.staticflickr.com/9/8094/8536670036_3803e9db6d.jpg

Figure 74 Brooklyn Battery Tunnel [55]

Figure 75 Other flooded road and subway tunnels[56], [57]

3.5.3 Potential Impacts

Transport network tunnels, unlike many other elements, are not easily affected by climate change impacts. These underground structures are often protected from weather due to their surroundings and location. Weather events which result in flooding are the most important impacts that could affect tunnels.

[55] http://www.online-literature.com/forums/attachment.php?attachmentid=8432&d=1351739591
[56] http://nypost.com/2012/11/13/brooklyn-battery-tunnel-to-be-reopened-soon-source/
[57] http://www.telegraph.co.uk/news/worldnews/northamerica/usa/9642268/Sandy-New-York-su8way-system-flooded-in-worst-ever-disaster.html

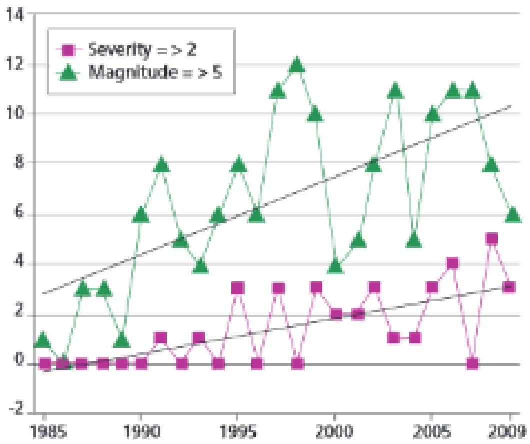

Figure 76 Example of a flooded tunnel [58] and Large floods in Europe 1985-2009[59]

3.5.3.1 Flooding

According to the New York City Hazard Mitigation Plan (De Blasio B, Bruno, J.F. for Office of Imergancy Management, 2014), flood events, the temporary inundation of normally dry land, can vary significantly in their causes, rates of development, duration, and geographic scale. Floods can be caused by excess water from oceans, rivers, groundwater, rainfall, or sewers and are commonly induced by a rain or storm event. Seasonal and intra-annual variations in tidal and hydrological cycles, along with effects attributed to climate change (such as sea level rise, intense precipitation, and more frequent, severe storms) can also contribute to flooding.

Some floods develop gradually, over a period of hours or days, such as those that can occur during hurricanes or other coastal storms. Other floods happen more quickly, sometimes in a matter of minutes, and are associated with a sudden event such as a thunderstorm. Similarly, the duration of a flood depends on many factors including paths for water to exit the flood are, such as land gradients, waterways, sewers, or porous soils.

3.5.3.2 Coastal flooding

Coastal floods affect areas along the ocean, bays, rivers, streams, or estuaries of tidal influence. They can be caused by storm surge from a strong coastal storm. When a storm approaches land, the storm surge piles up at the edge of the water body, raising water levels and leading to coastal flooding. Storm surges can cause flooding, or a rise in water levels without significant waves, or result in flooding accompanied by waves. With or without waves, coastal flooding can cause erosion and structural damage and create hazardous conditions, both on surface and underground. The salt water that comes with coastal flooding can ruin mechanical and electrical equipment and harm vegetation.

[58] http://commons.wikimedia.org/wiki/File:Ryde_Esplanade_railway_line_and_tunnel_flooding.JPG
[59] Large floods in Europe: NAS and MMI, 2013

3.5.3.3 Tidal flooding

Sea levels fluctuate due to gravitational forces and the orbital cycles of the moon, sun, and earth. Each day there are two high tides and two load tides. Flooding from high tides affects some low-lying sections, where neighbourhoods with extensive shoreline exposures are particularly vulnerable to this type of flooding.

3.5.3.4 Riverine flooding

Riverine flooding occurs when freshwater rivers and streams exceed local flow capacity and water spills over their banks. Flooding from large rivers are usually originated when large-scale weather systems generate prolonged rainfall over expansive areas. These same weather systems may cause flooding of smaller basins that drain into major rivers, contributing to riverine flooding. Narrow rivers and streams are susceptible to flooding from more localized weather systems that bring intense rainfall over small areas.

3.5.3.5 Inland flooding

Inland floods, or “flash floods”, can be caused by short-term, high-intensity rainfall, often associated with sudden small-scale thunderstorm or hurricanes and other large scale storms. Inland floods can also be caused by moderate rainfall over several days, typically brought on by weaker storms that drift slowly or stall over an area. Inadequate drainage can also contribute to inland flooding. In Europe, the report performed by EASAC, “Trends in extreme weather events in Europe: implications for national and European Union adaptation strategies” gathers data from diverse flood events since 1983 (

Table 6), linking it to the inflation adjusted damage and the number of fatalities caused by them.

Table 6 Floods in Europe. Source NAS end MMI, 2013

Floods in Europe with the highest (inflation-adjusted) losses			
Flood date	**Country**	**Inflation-adjusted damage (€)**	**Number of fatalities**
November 1966	Italy	10 billion	70-116
August 1983	Spain	2-6 billion	40-45
November 1994	Italy	4.5-10 billion	64-83
July 1997	Poland, Czech Republic, Germany	2-6 billion	100-115
October 2000	Italy, France, Switzerland	7.5 billion	13-37
August 2002	Germany, Czech Republic, Austria	15 billion	47-54
August 2005	Romania, Bulgaria, Switzerland, Austria, Germany	1.1 billion	53
May/June 2013	Central Europe	13 billion	25

3.5.3.6 Sea Level Rise

The project ***Risk increase to infrastructure due to sea level rise*** Jacob et al.,2000)developed an analysis about the consequences of climate change in the Metropolitan East Coast of U.S.A., studying transportation infrastructures such as bridge access roads, entrances to road and rail tunnels, including subways and ventilation shafts, but also non-transportation infrastructures such as storm sewers, wastewater processing plants and other critical infrastructures located at critical low elevations. They are vulnerable to climate-dependent sea level rise, which can cause flooding and hence can be subjected to related interruptions of services. They concluded that many elements of the transportation and other essential infrastructure systems in the MEC (Metropolitan East Coast) region, and even some of its regular building stock, are located at elevations from 1.83 to 6 m above current sea level. This is well within the range of expected coastal storm surge elevations of 2.44 to more than 6 m for eastern tropical and extra-tropical storms. Depending on which climate models will apply, the sea level rise over the next 100 years will accelerate and amount to at most 0.9 m by the year 2100.

Table 7 Estimates for recurrence periods for the years 2000 and 2100)

Estimates for recurrence periods for the years 2000 and 2100)			
Equivalent Saffir-Simpson Category*	Surge Height (m)	Average recurrence Period (years)	
		2000	2100
Extratropical Storm	2.44	20	6
1	3.10	50	15
2	3.35	100	30
3	3.96	500	150
3 – 4	4.27	1000	300
4	4.88	2500	800
*Using the year 2000 recurrence period for this column			

The methodology utilized takes into account the Metro New York Hurricane Transportation Study (MNYHTS, 1995), which takes a deterministic, worst-case scenario approach. The hurricane study computes the storm surge heights associated with worst-case storm tracks for hurricanes that measure category 1, 2, 3 or 4, respectively on the Saffir-Simpson (SS) scale, regardless of their frequency of occurrence (Table 7).

Results showed that the increase in surge heights between the decades starting in 2000 and 2090 amounts to about 1m. Surge heights associated with a recurrence period T at the beginning of this century (2000) will be reached at the end of this century with a surge of a recurrence period that is about 10 times shorter.

The other important pieces of information that MNYHTS compiles are the lowest critical elevations of transportation systems in the MEC region. The lowest critical elevations of key components of transportation systems are defined as the lowest points of entry to tunnels, subways or ventilation shafts. Or they are the lowest points of airport runways, roadways and bridge approaches where flooding to or above this level will severely affect, and for all practical purposes shut down, the systems' operations.

Note that for worst-case scenario storms stronger than Category 2 (in lower Manhattan zone analysis) entrances to subway, road or rail tunnels or ventilation shafts will be at or below flood levels, not to speak of the building stock and other assets that are located in the flooded areas.

MNYHTS (1995) illustrates the expected flood levels, Figure 77-Figure 80, in this area and at other key locations in New York and New Jersey by superimposing them onto photographs for selected facilities.

The leading on-line tunnelling magazine TunnelTalk (www.tunneltalk.com) provides a brief analysis about the vulnerability of cities to extreme weather events. They discuss Hurricane Sandy, in an issue focusing on the eastern coast of North America). The vulnerability of underground infrastructures in New York and New Jersey was exposed due to the flooding caused by the Hurricane Sandy. Despite the fact that road tunnels and subway stations returned to service within days after the flooding, the effects of the corrosive ocean water that flooded several operating systems and structures will last for years. The effects of the super storm were devastating during the worst days of this extreme event, flooding and damaging the underground transportation infrastructure. In addition other serious effects included:

- The escape of natural gas from ruptured supply lines.
- The contamination of floodwater from broken and backed-up sewer mains and treatment plants.
- The life threatening hazard of severed and fallen electricity power lines with fires started by surface electrical faults.

Figure 77 Potential Category 2 hurricane surge at South Ferry (Battery Station)[60]

Figure 78 Potential Category 2 hurricane surge at Hoboken Terminal [60]

Figure 79 Potential Category 2 hurricane surge at Manhattan Holland Tunnel entrance [60]

Figure 80 Potential Category 3 hurricane surge at Word Trade Center, West Street [60]

3.5.3.7 Evaluation of adverse impacts of extreme weather hazards on tunnels and underground structures

According to the “*Urban underground infrastructure and climate change*”, performed by Nikolai Bobylev, Table 8 summarizes climate change related threats to tunnels and underground structures and describes possible consequences of adverse external impacts on tunnels caused by these threats.

[60] Klaus H.Jacob, Noah Edelblum and Jonatahan Arnold.RISK INCREASE TO INFRASTRUCTURE DUE TO SEA LEVEL RISE Climate Change and Global City: An assessment of the Metropolitan East Coast (MEC) Region

Table 8 Impacts on tunnels. Vulnerability and damage

Climate-related threat	Impacts on tunnels	Vulnerability	Damage
Floods, Extreme rain	Inundation of underground structures through open structural elements, like entrances, sewers or ventilation shafts	High	Structural damage is low; damage to equipment is high unless waterproofing doors are used
	Inundation of underground structures through leakages in retaining structure due to high water pressure	Low	Low if leakages are not continues
	Suffusion of surrounding soil due to change in water level during the flood	Low	Extremely high, up to structural collapse
	Sewers and rainwater collectors overcapacity operation, which might result in their structural damage	Medium	Medium
Sea level rise, and subsequent rise of surface and groundwater levels	Structural damage due to changing soil stress-strain condition, "floating up" of underground structures	Low	Medium
Extreme atmospheric temperatures	Ventilation systems can become temporary not operational.	Low	Low
Extreme wind	Ventilation shafts can be structurally damaged	Low	Medium

It should be noted that Table 8 does not mention loss of land due to sea level rise. The extent of this loss would depend on the level of sea rise and protective measures, which would require permanent structural underground changes, e.g. redesigning entrances of the underground facilities.

Flooding appears to be the major threat to tunnels and underground structures. In the last decade of the 20th century, there have been four cases when flooding of urban underground rail systems have caused damage worth more than €10 million and numerous cases of lesser damage (Compton et al., 2002). Climate change has the potential to increase flooding risks in cities in three ways: from the sea (sea level rise and storm surges); from rainfall (for instance by heavier rainfall or rainfall that is more prolonged than in the past; and from changes that increase river flows) for instance through increased glacial melting (Satterthwaite, 2008).

Extreme weather events represent the major threat to tunnels and underground structures in the short term. Sea level rise of some meters represents the major threat to underground facilities in the long term. Major failures of underground structures due to sea level rise are unlikely, whereas minor damage is almost certain. This damage will be caused by exposure of previously "dry" parts of underground structures to groundwater, and increased hydraulic pressure to lower parts of the structures; both of these phenomena will result in leakages which need to be timely eliminated to avoid serious damage. Thus, a rise in sea level will require increased spending on underground facilities maintenance.

3.5.4 Remediation measures which increase resilience

In the report of urban underground infrastructure and climate change (Bobylev, 2009), adaptation of tunnels and underground structures to climate change is considered by means of structural, technical, and managerial measures. Adaptation of these underground facilities needs to be anticipatory, i.e.to take place before significant impacts of climate change are observed. Structural measures of adaption include strengthening waterproofing capacity of the structures, rigor maintenance and upgrading of sewers for transporting overcapacity amount of storm water. Storm water temporary storage underground tanks could be installed to mitigate impact of heavy rain falls. Structures needed to be checked and if necessary repaired or modified to withstand higher water pressure (and stronger wind in case of ventilation shafts).

Technical measures to combat extreme weather events like floods include installing waterproofing barriers and doors; increasing capacity of pumps, including installation of emergency reserve pumps in facilities inundation of which can bring extreme damage (e.g. critical infrastructure facilities).

3.5.4.1 SMART tunnel

The "Stormwater Management and Road Tunnel" or "SMART Tunnel", is a storm drainage and road structure in Kuala Lumpur, Malaysia, and a major national project in the country. The 9.7 km tunnel is the longest storm water tunnel in South East Asia and second longest in Asia.

The main objective of this tunnel is to solve the problem of flash floods in Kuala Lumpur and also to reduce traffic jams along Jalan Sungai Besi and Loke Yew flyover at Pudu during rush hour,

Figure 81. There are two components of this tunnel, the storm water tunnel and motorway tunnel. It is the longest multi-purpose tunnel in the world. It was opened on May 14th 2007, after 4 years of construction, it handles 30 000 cars per day and has been used 44 times to divert floodwater.

The tunnel has three modes of operation. In the first mode, under normal conditions where there is no storm, no flood water will be diverted into the system. In the second mode, when flooding occurs, the flood water is diverted into the bypass tunnel underneath the motorway tunnel. The motorway section is still open to traffic at this stage. In the third mode, when flooding is severe, the motorway will be closed to all traffic. After making sure all vehicles have exited the motorway, automated water-tight gates will be opened to allow flood waters to pass through. The motorway will be reopened to traffic within 48 hours of closure.

Figure 81 SMART Tunnel in Kuala Lumpur [61]

3.5.4.2 Port of Miami Tunnel

The Port of Miami Tunnel, Figure 82 is the result of a Public Private Partnership between Bouygues Travaux Publics and Meridiam Infrastructure (Private) and Florida Department of Transportation, Miami-Dade County and the City of Miami (Public).

The project consists of three main components: (i) two 1260m long, 13m wide tunnels below the Government Cut shipping channel; (ii) the connection of PortMiami on Dodge Island with I-395 via the MacArthur Causeway; (iii) and the widening of MacArthur Causeway Bridge, realignment of eastbound State Road A1A/MacArthur Causeway lanes and the reconstruction of Parrot Jungle Trail frontage road.

Marking each end of the tunnel are 24m tall portals designed by ArquitectonicaGEO, housing 50 ton flood gates to aid resilience in the event of a hurricane storm surge. These flood gates will come down in the event of a storm to prevent flooding of the tunnels.

[61] http://www.asianhumannet.org/english/newsletter/200901.html

Figure 82 Port of Miami tunnel flood gates [62]

3.5.4.3 Special case: immersed tunnels

According to Lunniss and Baber (2013) in their text: *Immersed tunnels,* the influence of rising water levels over time due to climate change must also be taken into account as this will determine the height of any flood protection measures when designing immersed tunnels. Global rates of sea level rise are compounded in some areas by the effects of isostatic readjustment following the melting of continental ice sheets created during the last glaciation. This is the effect of land, which had previously been pushed down under the weight of ice, rebounding upwards. However, rates of sea level rise are not uniform around the globe and even when isostatic effects are excluded, there are differences related to variable thermal expansion and large-scale oceanic currents.

Local subsidence due to faulting may also be a consideration. Not all waters are tidal. For a tunnel built beneath inland waterways, different conditions apply. In rivers, lakes, and canals, the water level will be dictated by rainfall and annual variations in flows. The relationship between water level increases with rain storm intensities that fit particular return periods is an important relationship to understand. The hydrographic data for design and construction comprises water levels, waves (length, direction, etc.), and currents, salinity/density of water, ice formation and tsunami possibility. Most of these conditions could be affected by climate change events.

[62] http://www.worldarchitecturenews.com/wanmobile/mobile/article/24629

3.6 Energy Lines including catenary, cables, OH lines, pylons etc.

3.6.1 Definition

Among all the different components of the electrical power grid infrastructure, power lines are always hit the hardest in extreme weather events. This is not surprising, as lines cover extensive lengths across both urban and country areas, and are quite exposed to weather. Comparatively, other components such as transformers and switchgear (breakers, protection relays, etc.) are more protected, being fenced at substations and sometimes housed under sheds. This reflects the fact that transformers and switchgear are more critical to the operation of the grid: the transmission network may typically afford to lose some redundant lines, but the loss of substation functionality is not desirable (substations are the nodes or "hubs" of the transmission grid). This is even more evident when considering generators: generating plants are comparatively more resilient under extreme weather threats, but when they do get affected, the impacts on the grid are still more serious than those created by lines or substation failures. For instance, in the US the "February 2011 Southwest Cold Weather Event" highlighted the problem of inadequate preparedness for extreme low temperatures in gas and fuel power plants: the generation shortfall was so serious that it endangered the stability of the whole grid. The incident proved so serious that North American Electric Reliability Corporation (NERC) ended up amending their reliability standards to include mandatory "winterization procedures" in the Emergency Operations Planning standards.

In this respect, this report will focus on lines and pylons, which suffer the most varied types of weather threats. Transmission and distribution lines carry electrical power over long distances. The most common type are overhead lines, especially in high-voltage transmission. Underground cables are much less common, except when considering last-mile sections in distribution networks, or some special high-voltage tie lines such as submarine power cables used to connect islands. Underground cables are virtually immune to most weather threats (except mudslides triggered by heavy rainfall), but they are not used very often because their price is 7 to 15 times that of overhead lines.

Additionally, most high and medium voltage lines are not shielded, again because of the economic trade-offs involved. They are simply isolated by maintaining a minimum separation between the different phases. If, for whatever reason, the phases touch each other or the ground, this produces a short circuit, which triggers ("trips") the protection relays and the line gets disconnected. In fact, the cables do not need to touch in order to produce the short circuit: given enough proximity, the short can be produced by electric arc (arc discharge). The higher the voltage, the higher the minimum distance needed to prevent arcing. This is actually a good way to tell the voltage level of a given line: the larger the distance between conductors (and the length of the suspension insulators), the higher the voltage of the line.

Figure 83 Typical high-voltage power conductor, consisting of seven strands of steel surrounded by four layers of aluminium [63]

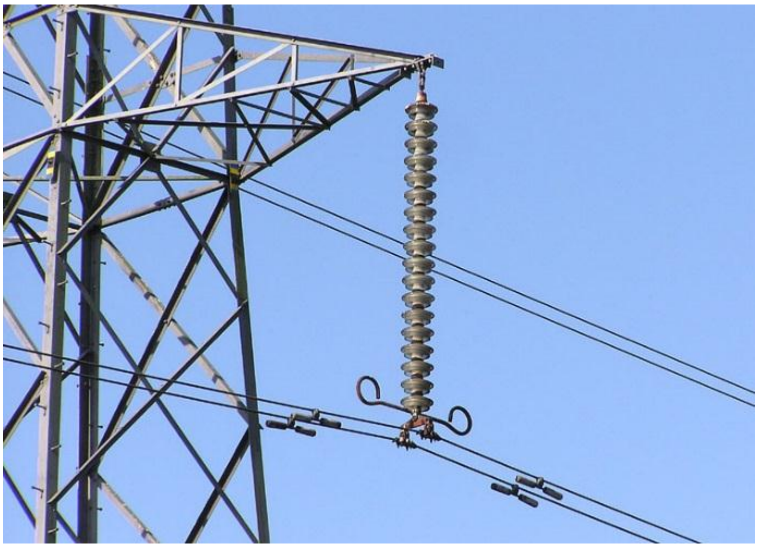

Figure 84 Modular suspension insulators used for high-voltage lines [64]

Rusting of the unshielded conductors is not in general a big concern, as most cables are made of aluminium (with a steel core). However, rusting of the pylon is a big problem, since most of them are made of steel. Transmission towers, commonly known as pylons, are used to support overhead power lines. The most common type is the steel lattice tower, but they come in a wide variety of shapes and sizes. Typical height ranges from 15 to 55 metres, though the tallest are the 370 m towers of a 2,700-metre-long span of the tie line connecting Zhoushan Island with mainland China. In addition to steel, other materials may be used, including concrete and wood.

[63] http://en.wikipedia.org/wiki/File:Sample_cross-section_of_high_tension_power_%28pylon%29_line.jpg
[64] http://en.wikipedia.org/wiki/File:Pylon.detail.arp.750pix.jpg

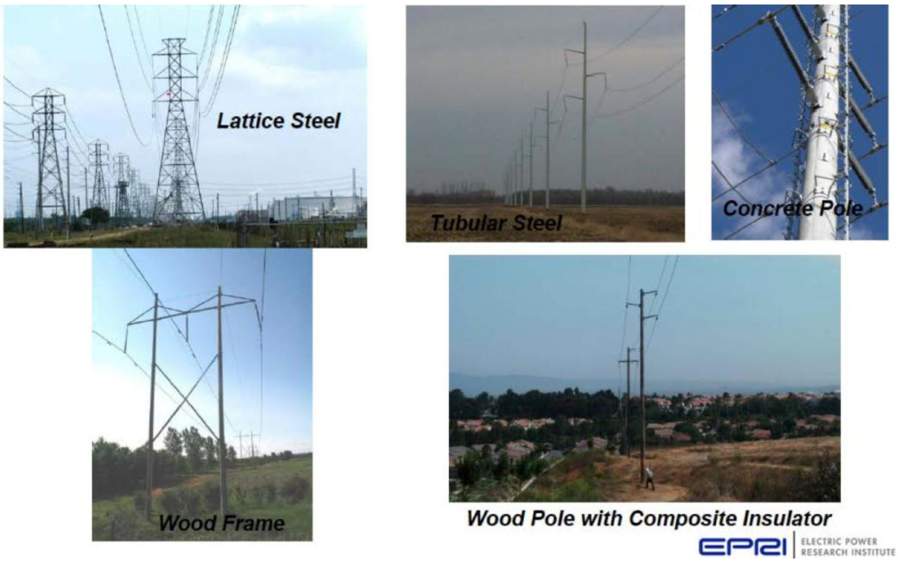

Figure 85 Different types of pylons [65]

In addition to the tower and the conductors, Figure 83-Figure 85, a third important element of any transmission or distribution line is the concept of "right-of-way" , Figure 86. In simple terms, the right of way is the strip of land immediately below and adjacent to a transmission line. The width of a right of way varies by the type of line – again, the higher voltage, the wider the rights of way. The typical corridor widths, unless otherwise specified in the right of way agreement, are as follows:

- 44 to 100 kV lines require a corridor of about 21 m or more;
- 110 to 250 kV lines require a corridor of about 46 m or more;
- 400 to 500 kV lines require a corridor of about 60 m or more;

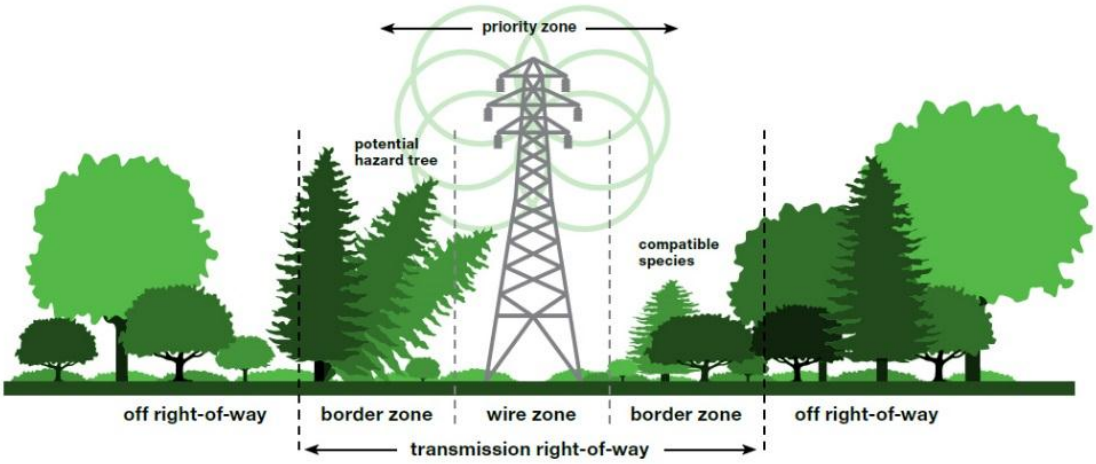

Figure 86 Schematic view of a transmission right of way [66]

[65] http://www.epri.com/Pages/Default.aspx

Regarding preparedness for extreme weather events, vegetation management of rights of ways is an extremely important issue which is evident from Figure 86.

3.6.2 Examples

3.6.2.1 Windstorms Lothar & Martin (France, 26-28 Dec. 1999)

Extra-tropical cyclones Lothar and Martin affected Western Europe on December 26-28, 1999. The wind fields from the two storms covered more than half of France and extended into Switzerland and Germany. The storms caught Europe by surprise. Meteorological forecasts failed to predict Lothar's dramatic inland intensification. Modern infrastructure such as electrical distribution systems, transportation, and communication lines were hit particularly hard, leading to several very large insured and uninsured losses throughout the industrial and public sectors.

The first event, Lothar brought hail and rain that crossed the northern part of France during the night of December 25th to 26th, 1999. The gusts of wind started on the Brittany Coast around 3.00am. Wind speeds of 170 km/h were recorded in Brest. The storm gained speed and power as soon as it crossed France. At Orly airport, a peak wind speed of 173 km/h was recorded; whilst 216 km/h was measured on the Eiffel Tower, 150 km/h at street level in Paris and 180 km/h in the Vosges Mountains. There is no record in the Meteo France archives of such a fierce weather event occurring. Martin was the second storm, hitting the southern part of France on December 27th around 5 pm. There, wind speeds of 150 km/h were recorded. Between them, these windstorms produced over €14.2 billion in economic damage, approximately €7.7 billion of which was insured. Windstorm Lothar alone represents the largest monetary insurance loss in European history. During the first storm, 30 people were killed. Damage was substantial: several houses and other buildings were partially or totally destroyed. Many roads, motorways and railways were blocked.

The electrical grid also suffered severe damages including: flooded substations, broken or tangled wires, flattened poles and twisted pylons. The interconnection grid was also badly affected: lines to Germany were temporary out of order. 5,500 medium and low voltage poles needed to be replaced. The storm also caused huge damage to forests. Some of them were completely ruined. Thousands of trees fell on MV and phone overhead lines. Air and railway traffic was severely disturbed. But most damage occurred on the Electricité de France (EdF) grid. Whilst, EdF had been prepared for ice storms (white frost or sticking snow on lines), such a severe situation was completely unanticipated. Nearly 3.4 million household customers were left without electricity. 35 EHV lines (a fourth of the total number) tripped due to protection relays. 180 HV lines were brought to the ground; more than 100 HV/MV substations were out of order. Innumerable lengths of MV and LV lines collapsed under falling trees.

In the morning of December 27, 1.4 million household customers were without electricity, mainly in the East, the North and in Paris suburbs. In these regions, the EdF grid was severely damaged: 120

[66] http://www.coned.com/publicissues/vm_transmission.asp

EHV pylons and 67 HV lines. After the second storm, the situation became worse. The total number of household customers without electricity on December 28 reached 3.45 million. It took nearly 10 days to bring the supply back to 97% of the affected customers.

3.6.2.2 Heavy snow/wind storms in Poland (November 2004)

On November 19th, three of the seventeen administrative regions in Poland, a part of Silesian and parts of the Malopolskie and Świętokrzyskie voivodships (provinces) were affected by a snowstorm with heavy snowfall and extremely strong wind storms. The weather conditions caused some serious disturbances in the operation of the national electricity system, both in the transmission grid (400 and 220 kV) and in the 100 kV sub-transmission grid, bringing about many serious damages both to national and international transmission lines. As a result of these disturbances, the dispatching services of the TSO (Transmission System Operator) and DSOs (Distribution System Operator) had to conduct a series of actions in a very short time in order to minimise the danger, to eliminate the disturbances and also to restore the dispatch of electricity to customers. The storm caused serious problems in the transmission system, with the disconnection of some 1,000 MW of load in the area covered by the Katowice distribution operator.

At the transmission level, problems started when, as the result of the storm, 400 kV and 220 kV cross-border tie lines with the Czech Republic tripped. In Poland, three 400 kV lines, six 220 kV lines, and one 400/220 kV 330 MVA autotransformer also tripped, as well as four smaller 220/110 kV 160 MVA autotransformers. The disconnection of the 400 kV line between Dobrzyn and Albrechtice (permanent since November 16, due to line damage at the Albrechtice station) had a significant influence on the sequence and evolution of this disturbance. The worst hit region was in southern Poland, where the operation of 110 kV lines is coordinated by the Katowice distribution utility. The loss of connections between the 110 kV distribution grid and the transmission 400 kV and 220 kV grids causes a large number of outages for final customers in a short period of time, due to the tripping of a radial 110kV connection which had no other redundant supply path. In the Świętokszyskie province, some 51 distribution lines and 434 transformer stations were destroyed. Around 13,000 customers suffered interruption of electricity supply. The failures were repaired within two days.

In the Silesia province, 6135 failures were recorded. As a consequence, 310,000 household and industrial customers, such as steel mills, water-conditioning stations, coal mines and cooling plants, lost supply. The loss of supply to the Water Production Plant Goczałkowice and Zawada for 24 hours caused shortages in fresh water supply to the Silesian area. Disturbances in the functioning of public transport also occurred. The traction power grid of railway traffic was also affected and 25 tramway traction lines were damaged. In the Małopolskie province, approximately 200,000 customers were left without electricity supply. On November 20th, 757 substations were out of operation and 57 MV lines were damaged. The following day, 1 HV line and 32 MV stations were still out of order. The largest number of failures was recorded in Kraków. On November 22, 1 HV line, 26 sections of MV lines and 24 MV stations remained out of service. About 4,000 customers were still without electricity. The faults in the MV network were repaired by November 23, and the HV line was put back into operation on the following day. According to the reports, the costs resulting from these events were estimated at around €20 M.

3.6.2.3 Tropical Storm Delta (Canary Islands, 28-29 Nov. 2005)

The tropical storm Delta was formed in the Atlantic, near the end of the hurricane season. Instead of moving west towards the Caribbean, as it is typical of these hurricanes, it first followed an erratic path before finally heading northeast, hitting the Canary Island with devastating consequences, Figure 87. The storm claimed nineteen lives and caused a total of €312 million damage throughout the archipelago. The electric infrastructure was hit particularly hard, mostly due to inadequate maintenance of pylons, as later enquiries revealed. About 300,000 electricity customers were affected by blackouts, which lasted several days.

Figure 87 Effects of tropical storm Delta in the Canary Islands, 2005 [67]

Thousands of homes were left without electricity as rusted pylons were blown down, Figure 88. The wind toppled or wrecked 39 high voltage pylons and no less than 103 medium voltage ones (1000-50000 V). The corroded condition in which the fabric of those structures were found to be in provoked little short of a major scandal and various institutions initiated legal proceedings and enquiries against Unelco-Endesa, the transmission and distribution utility.

Damage to grid infrastructure was estimated at some €12 million. Most of it was permanent damage to transmission lines, which are very costly and take a long time to replace. The Unelco-Endesa power company was forced to use temporary generators to boost power at sub-stations far from the main grid. In La Corujera in Santa Úrsula, these generators were poorly received and over 1,000 local residents claimed to be affected by the noise and pollution. Additionally, an improvised 66kV "underground" transmission line had to be laid down, running along a highway and covered by concrete. Even with all these efforts, 20,000 customers in the metropolitan area of Tenerife were

[67] http://www.noincineraciontenerife.com/noticias/938.htm

still without power four days after the incident. Some homes and businesses in Tenerife and La Palma had to wait the best part of a week for normal supply to be re-established. The blackout also affected to water supply (run by electric pumps) in several neighbourhoods in La Laguna, for a couple of days.

Figure 88 Toppled pylon in the Canary Islands event, clearly showing its rusted condition[68]

3.6.2.4 The great August 2003 blackout in northeast USA-Canada

On August 14, 2003, large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout. The outage affected an area with an estimated 50 million people and 61,800 megawatts (MW) of electric load in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, and New Jersey and the Canadian province of Ontario. The blackout began a few minutes after 4:00 pm and power was not restored for 2 days in some parts of the United States. Parts of Ontario suffered rolling blackouts for more than a week before full power was restored.

This high-profile case was not really caused by extreme weather, but it is nevertheless worth mentioning here. Investigations determined that the initiating incident resulted from the tripping of an important line, caused by overgrown trees. After this, a series of cascading failures followed. This highlights the importance of vegetation management in right-of-ways for lines. Since then, the regulatory bodies (FERC, NERC) established new rules and periodic compliance audits to make sure that utilities perform adequate maintenance.

[68] http://www.noincineraciontenerife.com/noticias/932.htm

3.6.3 Potential Impacts

In this section the impacts that the various weather threats may have on transmission and distribution lines are presented and listed approximately in order of likelihood:

- **wind storms** affect overhead lines typically by bending or toppling power line towers, bending or toppling trees over lines, or swinging lines violently and causing electrical faults. The damage to towers (pylons), either directly or indirectly by fallen trees, can be permanent. (Note: we include here hurricanes, tornadoes, and tropical cyclones). ;
- **ice/wet snow storms** can cause ice to grow on power lines, which may make the line crumble under its weight, or whip violently when the wind blows large chunks of ice off the line.
- **extreme heat** waves cause more strain on the grid than cold waves in terms of peak demand, because in contrast to heating, almost all cooling systems run on electricity. Aside from peak demand, extreme heat is a risk to congested transmission lines, due to the reduction in capacity (lower thermal limits due to less thermal dissipation) and to line sagging (dilated lines may cause faults by short circuiting to vegetation below).
- **lightning** affects mainly overhead lines and unsheltered transformers. Proper grounding techniques of pylons, protection relays, and automatic reclosers minimize this risk. However a high concentration and concurrence of lightning-triggered tripping may put the grid at risk.
- **flash floods** are a very high risk mainly for generator plants, but it could also affect pylons with weak foundations, causing permanent damage to the line.
- **wild fires** may affect mainly unsheltered transformers sitting on ground level or on poles, and overhead lines. Proper maintenance of vegetation in rights-of-way for lines and around substations should lower this risk.
- **sand storms**, though not a likely event in the EU countries, but a sandstorm can affect power transmission lines severely, directly or indirectly by fallen trees, just like windstorms.

3.6.4 Remediation measures which increases resilience

The main types of prevention and mitigation measures for common extreme-weather threats that affect OH lines & transformers can be grouped as follows:

- Rights-of-way maintenance: vegetation (addresses all, except extreme heat);
- De-icing & anti-icing measures (addresses ice storms);
- Line sagging prevention/mitigation (addresses extreme heat);
- Tower inspections and maintenance (addresses all, except extreme heat or wildfires).

The rest of the measures are more technical in nature: they consist in traditional electrical engineering best practices for proper grounding and relay protections for lines. They are a given; therefore these techniques will not be discussed here.

3.6.4.1 Rights of ways maintenance

Proper maintenance of right-of-ways addresses most of the above weather threats, except maybe extreme heat.

Regular maintenance of vegetation, Figure 89, within the rights-of-way is necessary to avoid disruption to overhead power lines and towers. Unchecked growth of tall trees and accumulation of vegetation within rights-of-way may result in a number of impacts, including power outages through contact of branches and trees with transmission lines and towers; ignition of forest and brush fires; corrosion of steel equipment; blocking of equipment access; and interference with critical grounding equipment.

Regular maintenance of rights-of-way to control vegetation may involve the use of mechanical methods, such as mowing or pruning machinery, in addition to manual hand clearing and herbicide use. Vegetation management does not eradicate all vegetation, but instead aims to maintain trees and plant growth that may negatively affect infrastructure at a safe threshold. These thresholds depend on the voltage level of the line, as explained above, and also on the typical swings and sags of the line depending on the expected wind and temperature extremes.

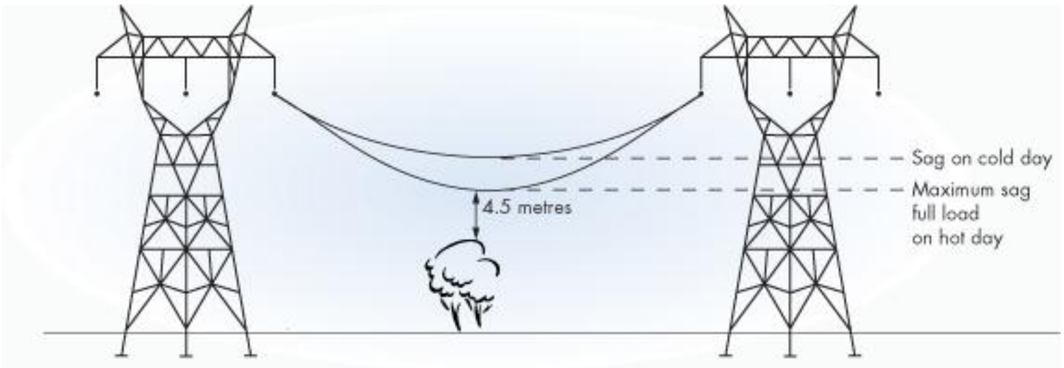

Figure 89 Example of vegetation height threshold, considering maximum expected line sag [69]

Recommended measures include:

- Implementation of an integrated vegetation management approach (IVM). The selective removal of tall-growing tree species and the encouragement of low-growing grasses and shrubs is the common approach to vegetation management in transmission line rights-of-way. Alternative vegetation management techniques should be selected based on environmental and site considerations.
- Mowing with heavy-duty power equipment may be used to control growth of ground covers and prevent the establishment of trees and shrubs in the right-of-way. Herbicides, in combination with mowing, may control fast-growing weedy species that have a potential to mature to heights over those permitted within the right-of-way. Trimming and pruning may be utilized at the boundaries of rights-of-way to maintain corridor breadth and prevent the

[69] http://www.hydroone.com/OurCommitment/Environment/Page

encroachment of tree branches. Hand removal or removal of vegetation, while labour intensive, may be used in the vicinity of structures, streams, fences, and other obstructions which make the use of machinery difficult or dangerous.

- Removal of invasive plant species, whenever possible, cultivating native plant species

An integrated approach to vegetation management may indicate that the use of herbicides is the preferred approach to control fast-growing vegetation within transmission and distribution rights-of-way. In such cases, they should be used in conjunction with environmental regulations (e.g. avoid their migration into off-site land or water environments).

If underlying growth is left unchecked, or slashing (wood debris) from routine maintenance is left to accumulate within right-of-way boundaries, sufficient fuel can accumulate that may promote forest fires. Recommended measures to prevent and control risk of forest fire include:

- Monitoring right-of-way vegetation according to fire risk;
- Removing blowdown and other high-hazard fuel accumulations;
- Time thinning, slashing, and other maintenance activities to avoid forest fire seasons;
- Disposal of maintenance slash by truck or controlled burning (observing the local requirements regarding burning, such as fire suppression equipment requirements, fire watcher monitoring, etc.);
- Planting and managing fire resistant species (e.g. hardwoods) within, and adjacent to, rights-of-way;
- Establishing a network of fuel breaks of less flammable materials or cleared land to slow progress of fires and allow firefighting access.

Figure 90 Rights-of-way of a high voltage transmission line [70]

[70] http://www.tva.com/power/rightofway/anatomy_row.htm

3.6.4.2 De-icing & anti-icing

De-icing and anti-icing measures address the threats associated with mainly ice storms and snow storms.

Icing formation on structures and power lines is an important consequence of extreme weather that causes damage in many countries. Accumulated ice can weigh the lines down and cause ground faults. Also, ice suddenly breaking off the line can make the line whip and snap. On lattice towers accumulated ice can add a considerable amount of weight and make the tower crumble.

Power lines are usually built following climatic hardiness rules (IEC, 2003), however in many countries, rules are only based on rough climatic evaluation by the altitude and latitude of the terrain where the power line will be built. In many countries where power line icing is a relevant problem, some strategies are taken into account in order to mitigate or avoid the effect of this phenomenon on the reliability of the power supply service. A wide presentation of these techniques can be found in the specific Cigré Report (Cigré 2009). The strategies can be classified in four groups:

- Passive methods: they do not require an external source of energy but use only natural forces such as wind, gravity or solar radiation. Consequently, they can function on both energized and non-energized phase conductors as well as ground wires. This group includes most of the anti-icing methods used to prevent or reduce the accretion of wet snow and ice on conductors. For instance, a well-known method among these consists in using counterweights to increase the torsional stiffness of conductor spans. Field observations in Japan, Iceland and France on wet snow have shown that this device can limit the formation of cylindrical deposits of wet snow by limiting the rotation of a conductor resulting from eccentric snow loading on its windward side. With highly eccentric snow loadings, shedding caused by gravity and wind forces is facilitated.

- Active coatings and devices: Methods based on active coatings are active methods requiring some electrical energy to be effective. For instance, one method is based on the use of a ferromagnetic coating for the purpose of sustaining a positive temperature of the energized conductor surface. This method, known as LC-Spiral Rod method, has been implemented successfully in Japan. These spiral rods have been manufactured and installed for more than 20 years to prevent accidents caused by the sudden fall of large chunks of snow.

- Mechanical methods: In most cases, mechanical methods can be considered as de-icing methods as they are used to speed the shedding process after snow packs or ice have formed on conductors and ground wires. It has been demonstrated that mechanical methods require around 100,000 times less energy than thermal methods to force ice shedding. Generally, most of the mechanical methods are based on two strategies. One strategy consists in breaking the ice by scraping it, and the second in releasing energy from shock waves, vibrations or ground wire/conductor twisting to break and pull off the ice. One of the main advantages of mechanical methods is their relative ease of application compared to thermal methods. In fact, mechanical methods are those preferred for timely and fast intervention to de-ice short critical sections of a power network. However, in general, these methods are to be avoided with ground wires carrying communications, as bending of the cable, due to the presence of the de-icing mechanism, can damage the optical fibres.

- Thermal methods: Heating of line conductors or ground wires to prevent ice accretion or for de-icing purposes is more expensive, but it is recognized worldwide as the most efficient engineering approach to minimize the consequences of severe ice storms on overhead lines. Thermal methods include all methods causing the ice to melt in order to force shedding. Some of these methods can be used for anti-icing purposes in order to prevent supercooled water droplets from freezing during their impact on the conductor surface. In that case, less energy is required for anti-icing than for de-icing. Thermal methods can be divided in two categories: (i) methods based on pure Joule effect, and (ii) methods based on dielectric losses, radiative waves and external heat sources.

Figure 91 Power lines covered in ice near the village of Skala in Poland. Around 27000 people were left without electricity due to electrical cables breaking from the weight of accumulated ice, in January 21, 2010 [71]

[71] http://www.telegraph.co.uk/news/picturegalleries/picturesoftheday/7043431/Pictures-of-the-day-21-January-2010.html?image=2

Figure 92 Line sag produced by the weight of ice produced a ground fault in this medium-voltage line [72]

3.6.4.3 Line sagging prevention/mitigation

Line sagging prevention/mitigation addresses mainly extreme heat. When lines carry electric power, they heat up due to the Joule effect, since they have some non-negligible resistance. The cables then dilate, causing sagging, Figure 93. Under extreme heat weather, particularly with low wind speeds, the line exchanges a lot less heat with the air around it, and the dilation could reach dangerous levels. Short of re-fitting the line with new cables (re-conductoring), some mitigation measures exist:

- Static re-rating of the line: This consists in re-measuring the actual physical parameters of the line, in order to measure the real thermal capacity limits ("ampacity"). This could be useful for very old lines whose properties may have changed with ageing.
- Dynamic re-rating: this is a more useful technique. It measures the effective line rating in real time, by electrical methods, thus taking into account the dynamic thermal properties (i.e. the level of heat dissipation at a particular point in time, which depends on the wind and solar irradiation).
- Real time monitoring: install devices to monitor and measure line sagging in real time. This is of course more expensive and cannot be deployed extensively.
- Sagging Line Mitigator (SLiM): a novel mechanical device that is purely passive. It automatically decreases the effective length of conductor in the span, counteracting the thermal expansion of the conductor.

[72] https://s-media-cache-ak0.pinimg.com/originals/fd/72/25/fd72258efdf1c0eb60c4c5e01515a857.jpg

Figure 93 Excessive line sag produced by thermal effects [73]

3.6.4.4 Tower inspection and maintenance

Proper maintenance of towers addresses most of the weather threats with the possible exception of extreme heat.

Towers are designed to withstand quite severe weather; in fact they should always be designed to withstand the expected extreme values at the location where they are built. However, these investments typically last more than 40 years, and they need periodic maintenance.

Maintenance should check at least for:

- Rusting: towers are built with high quality steel and they may have anti-rust coating, but nevertheless they should be checked for rusting, especially near coastal areas, Figure 94.
- Grounding: the grounding cables should be checked in order to ensure proper protection against lightning.
- Check for damaged or weak foundations. This includes checking for possible permafrost melting, particularly in Nordic countries.
- Check and clear birds' nests: big birds such as storks have quite long wingspans and they can easily cause short-circuits.

[73] http://mrtremblaycambridge.weebly.com/p5-matter-and-thermal-properties.html

Figure 94 Extreme rusting in a steel lattice transmission tower [68]

3.7 Dams

3.7.1 Definition

As a result of progress in engineering techniques and the advent of new construction materials, dams have been continuously growing in size with the result that very large dams have now been developed, these include:

- The "Three Gorges" dam in China, Figure 95a, which is 185 meters high and 2.3 km long,
- The "Akosombo" dam in the Volta River, Figure 95b, which was built between 1961-1966 and has a length of 700 m and a height of 134 m.
- In Europe, there are also important dams like the "Alqueva Dam" with 4150 hm^3 capacity, "La Serena" with 3219 hm^3 and "Alcantara" with 3160 hm^3.

(a) (b)

Figure 95 Three Gorges Dam (a) [74] and Akosombo Dam (b) [75]

Depending on their shape, dams can be classified into six types:

- Gravity dams
- Buttress dams
- Arch dams
- Embankment dams
- Arch-gravity
- Mixed

Arch-gravity dams and Mixed dams which derive from the combination of the previous types.

Depending on the construction material used, dams can be classified into three types:

- Masonry dams
- Concrete dams

1[74] http://www.businessinsider.com/chinas-enormous-three-gorges-dam-is-turning-out-to-be-a-huge-mistake-2012-14?op=1

[75] http://en.wikipedia.org/wiki/Akosombo_Dam

- Embankment dams wich also can be divided into earth-fill dams and rock-fill dams (including those with a concrete or asphaltic face).

According to the type of the break they are classified in two types:

- Instant breaking (Masonry and concrete dams)
    - Total breaking (Arch dam)
- Partial breaking/ Partial breach (Buttress and gravity dams) Progressive breaking (Embankment dams).

Instant breaking can occur within minutes, since a crack occurs when the dam collapses completely. According to the previous dams-type summary, the arch dams suffer from complete breaking while buttress or gravity dams break partially. On the other hand, dams constructed with loose material have a slower and progressive failure until total breaking occurs, although the effects of this failure are as dangerous as the instant breaking dams.

In Spain, in order to classify dams for further risk analysis, a dam's classification technical guide by Ministerio de Medio Ambiente (1996) "Clasificación de presas en función del riesgo potencial" has been drawn up to facilitate the implementation of the basic guideline for planning civil protection procedures and technical regulations. This guide starts with a dam's shortlist that is focused on dam's parameters (height, length, volume of dammed water, drainage capacity and economic potential danger or damage downstream). Those dams within the shortlist are enumerated below and should be thoroughly studied. This document focuses on classifying the dams according to their potential risk. A classification based on how they can pose a threat to inhabitants, city centres, services, environment, cascading effects, etc.

- Large dams, that are or over 15 metres high between the foundation and the crest level, or more than 10 metres high and over 100,000 m^3 capacity, or have other parameters that are considered an important risk to safety or public economy.
- Dams which don't have " Large dams" characteristics, and are over 10 metres and less than 15 metres, and have or a crest length over 500 metres, or an outlet works capacity over 2000 m^3/sec.
- In addition, all dams not included in the two aspects described before, which could generate potential risk downstream, have to be studied.
- ny dam that seems to be important for the National Hydraulic Administration can be introduced in the shortlist if they consider it necessary.

Once the shortlist is defined, as is recommended in the guide, the dam analysis is performed in order to classify them by the impact of the dam's collapse or operation failure:

- **Type A**: Essential services or urban areas could be globally affected. Dam failure could produce very important damages on materials and environment;

- **Type B**: A reduced housing number could be affected. Dam failure could produce important damages on materials and environment;

- **Type C**: Human casualties could happen but only incidentally. Dam failure could produce moderate damages on materials and environment. Within this type, all dams that are not classified as Type A or Type B, are registered.

The surrounding population lives under potential risk of disease by dam failure. This is a main factor under consideration for this evaluation. The classification considers a dam to be type A if urban areas can be affected if it breaks, type B if only a reduced number of dwellings might be affected and type C if lives are only incidentally affected. Therefore, human life is the first parameter to be considered in the classification process.

The classification is based on a progressive evolution of the potential damage from category C to A. This means that the first step when classifying a dam is to analyse if it meets the requirements of Type C dams. Failure to meet the criteria for Category C, means that the dam should be included in Category B or A. Type B criteria is analysed and, if not complied with, the dam should be classified as type A.

To summarise, the four principal damage types analysed and used for performing the classification are:

- Potential risk to human lives. Population at risk.
- Damage to essential services.
- Damage to property.
- Environmental damage.

The analysis is performed by evaluating the category associated with each of the potential types of damage, without considering their possible combinations , and focuses on the damage that could occur in case of dam breakage.

To perform this analysis, some basic criteria of different impact assessment is summarized below:

- **Impact to human lives**, distinguishing between serious conditions in urban areas (affecting more than five inhabited dwellings and generating risk to people lives depending on the depth and speed of the wave, See Figure 96, impacts to a small number of dwellings, or incidental casualties.

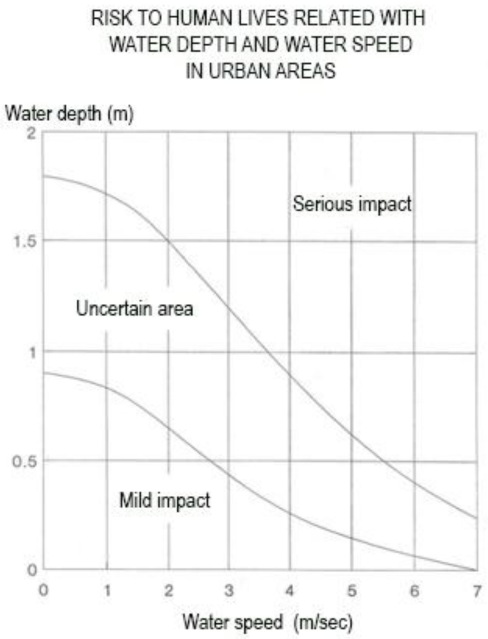

Figure 96 Risk to human life related to Water Depth and Speed in urban Areas [76]

- Urban areas: set of at least 10 buildings or lower if the population inhabiting the same exceeds 50 inhabitants. Isolated buildings closer than 200 meters from the boundaries of the set, are included, whereas industrial areas, sports facilities, bridges, etc. will be excluded.
- Low number of dwellings (between one and five inhabited houses).
- Incidental casualties: is not considered if permanent residences, campgrounds stables or areas where crowds of people are usually located, are affected.

- **Essential services impact**. Essential services are those which are indispensable for the development of normal human and economic activities of a population, of at least 10,000 individuals. Serious impacts are those which affect one of the services within the following shortlist so hard that they cannot be repaired.
  - Water supply and sewerage system.
  - Energy Supply.
  - Sanitary system.
  - Communications system.
  - Transport system.

[76] Ministerio de Medio Ambiente, Dirección General de Obras Hidráulicas y Calidad de las Aguas
Guía técnica: Clasificación de presas en función del riesgo potencial

- **Property damage impact**, this should be measured in quantifiable economic terms, so casualties or environmental damage are not included.

The property damage will be assessed for the following categories:

- Damage to industries and industrial parks.
- Damage to rustic properties.
- Damage to crops.
- Damage to infrastructure

Table 9 Classification of Material Damages

MATERIAL DAMAGES CLASSIFICATION			
Elements	**Potential damages**		
	Moderate	**Important**	**Very Important**
Industries, industrial estates and rural property	Number of facilities < 10	10 < Number of facilities< 50	Number of fatilities> 50
Rainfed crops	Area < 3000 Has	3000 < Area < 10000 Has	Area > 10000 Has
Irrigated crops	Area < 1000 Has	3000 < Area < 5000 Has	Area > 5000 Has
Roads		Autonomous Community general road network	State general road network and Autonomous Community basic road network
Railways		Narrow gauge rail	Broad gauge and High-speed rail

- **Environmental impact** on artistic and cultural-historical references. Those two aspects should be differentiated for assessment purposes.

Only damages which are substantially different from those associated to the natural water regime will be considered as potential environmental damage.

- **Impacts not covered by any of those described above** should be classified if they can aggravate the effects of dam breakage itself (e.g., Dam downstream may have domino effect, special cases as nuclear power plants, etc.).

The guide also defines **criteria for potential failure analysis**, indicating, for classification purposes, that only potential breaking is considered, excluding any malfunction. Two possible general scenarios are indicated.

- Single dam breakage: This scenario should be defined by the location of the reservoir and hydrological conditions at the time of the breakage (analysing the two extreme situations, breakage with or without flood).

- Breakage without flood: Reservoir is at its maximum normal level of operation and there is no incoming flood.

- Breakage with an incoming flood: The dam's outlet works are working at their maximum capacity and water surface is at the crest level.

- Chained dam breakage (domino effect): In this general scenario, the downstream flooding effects should be considered through two scenarios:

    - First sub-scenario: The downstream reservoir can absorb the wave that was originated on the upstream dam breakage still complying with the conditions for which it was designed and, even if the second dam reaches crest level proximity, it is not likely to have floods simultaneously in both dams. In this case, the chained dam breakage downstream would not occur, and each dam would be classified, focusing only, on their own potential impacts independently.

    - Second sub-scenario: The downstream reservoir cannot absorb the wave that was originated on the upstream dam breakage, producing overtopping over the crest level. This approach gives rise to a new scenario, which is corresponding to the breakage with reservoir at the crest level, plus the break wave from the upstream breakage dam.

Regarding the dam breaking time, and continuing with criteria for potential failure analysis, the guide explains that the breaking time, Table 10, will depend on the shape and dimensions of the crack and the dam typology (as it was previously described on the present document, the erodible dams will have a progressive breakage, and concrete or masonry dams, will have an instant breakage).

Table 10 Dam Breakage Time and Crack Features

Dam Typology	Dam breakage times	Crack shape and dimensions
Arch dam	5 - 10 min	Complete breakage, following the dam natural downstream boundary shape. Trapezoidal geometrisation could be accepted.
Gravity and buttress dams	10 - 15 min	Rectangular • Crack depth: until contact with the riverbed at the toe of the dam. • Crack Width: the higher of the following two values: 1. 1/3 crest length. 2. Three construction blocks.
Embankment dams	**T (h) = 4,8 · V0,5 (Hm^3) / h (m).** If the above equation leads to more than five hours as a result, the breaking time should be evaluated with particular attention.	Trapezoidal • Crack depth: until contact with the riverbed at the toe of the dam. • Average crack width **1. b (m) = 20 (V (hm3) - h (m)) 0.25** • Slope: 1: 1 (H: V).

Also, the flood wave propagation criteria should be studied. This will depend on:

- The *valley geometry*, requiring that all profiles used in the analysis, must be defined by at least three contour lines (two equidistant). These criteria define the minimum study scale to be used, Table 11:

Table 11 Definition of minimum study scales

Minimum water depth (m)	Maximum equidistance	Associated scale
1	0,5	1:500
2	1,0	1:1000
4	2,0	1:2000
10	2,0	1:5000
20	10,0	1:10000 (1:25000)
40	20,0	1:50000

- The main channel roughness, obstructions and local phenomena roughness are other facts that intercede on the wave flood propagation criteria. Roughness coefficient is obtained empirically with bibliographic database such as proposed by the USSCS method or the values provided by Ven Te Chow.

In addition, the analysis of the geometry of the valley and the survey of the area allows to locate singular works in terms of important channel obstructions. The obstructions is only considered if the following two circumstances happen simultaneously:

Obstructions are considered if:	The ratio between obstructed area and the total channel area exceeds 20%.
	Create a temporary reservoir of relative important magnitude, representing 5% of the flooding wave volume.

Continuing and finishing with the criteria for potential failure analysis, the guide defines the criteria for estimating **risks downstream** and **early warning time**.

Having explained the functioning of the grading method, the most common causes should be mentioned (including design causes) of dam failures that can generate potential risks in order to reduce and mitigate those risks.

Most frequent causes of dam failures:

- Overtopping of a dam is often a precursor of dam failure. Overtopping can be due to inadequate spillway design, debris blockage of spillways, or settlement of the dam crest;
- Foundation defects, including settlement and slope instability, are another cause of dam failures;
- "Piping", that is internal erosion caused by seepage, is the third main cause. Seepage often occurs around hydraulic structures, such as pipes and spillways; through animal burrows;

around roots of woody vegetation; and through cracks in dams, dam appurtenances, and dam foundations;

- The other causes of dam failures include structural failure of the materials used in dam construction and inadequate maintenance.

However, the most important "Failure Modes" for the RAIN project are linked to meteorological impacts or environmental cases, and were agreed by ICOLD (International Commission on Large Dams). Those "Failure Modes" are listed below:

1. Overtopping due to hydrological causes;
2. Slope instability in the reservoir (Insufficiency of Shear Strength);
3. Dynamic Instability (Insufficiency of resistance to the seismic action);
4. Elastic Instability (structural Insufficiency) or dam internal erosion (Insufficiency of dam Internal stability);
5. Static-sliding instability or dam slope instability (Insufficiency of Shear Strength), being or not being able to affect the foundation, in the latter case;
6. Internal erosion foundation (Internal Stability failure in general, including problems associated with solubility, Siphoning, filtration, etc.).

Note: When two "Failure Modes" are jointly considered, the first application will be used for masonry or concrete dams, and the second one would be the "equivalent" to embankment dams.

3.7.2 Examples of Dam Failures

In Spain, since 1799, 10 dams have failed, Table 12. This represents an overall percentage of 0,9%, slightly lower than the world average.. The most frequent cause of failure has been that of overtopping, accounting for 30% of the failures, which represents almost 0,3% of the existing dams. All these failures have occurred in embankment dams.

Table 12 Examples of Dam failures in Spain

Name	Type	H (m)	V (hm3)	Constr. (year)	Failure (year)	Cause
El Gasco	PG (M)	54	4,6	-	1799	Failure of downstream slope
Puentes	PG (M)	50	52	1791	1802	Piping of the foundation
Granadillar	PG (M)	20	0,1	1933	1933	Instability of the slopes
Xuriguera	PG	42	1,1	1902	1944	Sliding of right bank of dam

Vega de Tera	CB	34	7,3	1956	1959	Collapse of the buttresses
Odiel-Río Tinto	ER	35	3,3	1970	1968	Overtopping
Jerte (Cofferdam)	ER	16	-	-	1977	Overtopping
Tous	ER-PG	71	51	-	1982	Overtopping
Fuentesagrada	MV	20	0,06	1958	1987	Deterioration of concrete and expansive phenomena
Orjales	MV	13	0,02	1958	1994	Collapse of the buttresses
PG – Gravity dam TE – Earthfill dam		PG (M) – Masonry gravity dam ER – Rockfill dam				CB – Buttress dam MV – Multiple arch dam

3.7.2.1 Tous dam failure (20 October 1982)

On October 19th 1982, an extreme meteorological phenomenon called "la gota fría" hit the Mediterranean coast. This phenomenon happens, with different intensity, almost every year and normally by the end of the summer or the beginning of the autumn. It is caused by an air isolated depression at high levels (between 5000 and 10000 meters), whose core consists of a very cold air mass that generates cold rain and storms. The night from the 19th to the 20th of October, an impressive mesoscale convective complex that remained almost static over the zone produced a deluge that lasted the whole day, increasing the flow volume of the nearby river "Júcar".

The rainfall exceeded 100 mm in most of the Jucar basin and 600 mm in an area of 700 km² upstream of the reservoir. This caused a large influx of water, which made unusable the generator in charge of opening the spillway gates.

The arrival of a new aid generator took longer than expected. In addition, the dam staff were not sufficiently qualified, forecasts of torrential rain were not properly warned and some mechanical systems were not in optimal conditions, hampering the gates manual opening.

As a result of the above, the water level rose in the dam by 20 meters in a mere 12 hours, reaching the dam crest. This was despite the last minute opening of the floodgates. In addition the dam had an insufficient discharge capacity to cope with the unexpectedly high incoming flood. . The water overtopped the dam and, since it was a rock fill dam, water eroded the downstream slope causing a progressive breakage and finally, its collapse, at 19:15 pm. The downstream flood reached 16,000 m³ / s, one of the largest recorded in Spain, devastating the regions of "Ribera Alta" and "Ribera Baja".

The nearest towns Figure 98 (Figure) reached a water level of eight meters causing structural damage in most buildings, generating economic losses estimated in 330 million Euros at that time and nearly 30 casualties.

(a) (b)

Figure 97 Tous dam breakage[77],[78]

Figure 98 “La Pantanada de Tous” [79]

3.7.2.2 Malpasset Dam

Malpasset dam is a concrete arch dam built in the south of France in 1954 which collapsed in 1959, causing nearly 420 casualties. The most likely cause for the disaster was a tectonic fault not detected by the insufficient geologic investigation.

Furthermore, 24 hours before the collapse, abundant rains occurred and although the water level rose, the authorities denied the request to open the spillway because a road was being built downstream, and they didn’t want to inundate it.

[77] http://www.abc.es/fotos-comunidad-valenciana/20121013/imagen-rotura-presa-tous-1503489423647.html
[78] http://www.impact-project.net/images/tous_dam.jpg
[79] http://www.tiempo.com/ram/10372/inundaciones-de-octubre-de-1982-la-pantanada-de-tous-2/

Figure 99 Malpasset dam [80]

Discharge valves were finally opened, but at a small rate, not enough to empty the reservoir on time. Water pressure in the foundation is alsoconsidered another cause for the disaster.

3.7.2.3 Pantano de Puentes Dam

The "Pantano de Puentes" dam is located in Spain, in the region of Murcia. The first construction began in 1647 and while under construction, was destroyed due to a large flood in 1648.

Years later, in 1785, the construction of the second dam, called “Puentes II”, cpmmenced. In 1802 the dam collapsed due to rains, floods and especially, a foundation failure. This failure was predicted by some engineers, as the dam foundation was located on sands, but the contractor responsible for the construction disregarded those negative reports. This collapse caused over 600 fatalities, the worst dam disaster registered in Spain.

Figure 100 Second dam [81]

In 1881, the third dam (Puentes III) was built, located about 200 meters downstream away from the previous location, on a more suitable spot.

[80] http://en.wikipedia.org/wiki/Malpasset_Dam
[81] https://elrincondecmc.wordpress.com/trabajos/trabajo-principales-inundaciones-en-espana/

Finally, in 1993, a heightening project for Puentes III dam was approved, constructing Puentes IV in the same place, rendering the third dam redundant.

Figure 101 Third and fourth dam [82]

3.7.3 Potential Impacts

3.7.3.1 High rainfall

High rainfall can pose a serious threat to dam stability, some of the potential impacts based on dam type are summarised in Table 13, the operational impacts are considered in Table 14.

Table 13 Potential Impact According to the type of structure for Heavy Rainfall

Type of structure	Sub-type	Potential Impact
Erodible	Clay core and homogenous Clay construction	More rapid fluctuations in operating water levels possibly leading to increases in pore pressure. This includes rapid fill or emptying (as an operational response) in advance of heavy rains. Risk of piping failure or mass instability as a result.
		Water levels above design levels results in a risk of overtopping and erosion of the downstream face.
		Direct rainfall may cause erosion of dam face (normally downstream).
		Higher water levels may lead to an increase in seepage (flow paths may

[82] https://www.chsegura.es/chs/cuenca/infraestructuras/embalses/embalsedePuentes/antecedentes.html

		exit higher up on downstream face).
		For reservoirs sited in floodplains, elevated flood risk may lead to greater erosion and damage to reservoir toe. Long-term repeated, seasonal exposure to flooding could reduce reservoir toe integrity.
	HDPE liner	Water levels above design levels results in a risk of overtopping and erosion of the downstream face.
	Asphaltic concrete	When co-incident with wind can result in wave action at higher levels on liner and dam.
Non-erodible	Masonry, concrete	Water levels above design levels results in a risk of overtopping.
		Water levels above design levels result in risks of sliding and overturning.
Spillways		High flows and water levels exceeding spillway designs can result in spillway failure.
		High rainfall hence flows may increase transport of debris, potentially damaging or blocking spillway.
Auxiliary structures		High rainfall hence flows may increase transport of debris, potentially damaging dam components.

Table 14 Potential Impact According to the affected Dam performance for Heavy Rainfall

Operational use	Potential Impact
Flood detention	Increased flow into reservoirs increases flood risk: increased storage requirements or less well managed floods.
	Increase in sedimentation during flood events could lead to reduction in flood storage capacity and/or blockage of spillways due to increased mobilisation of vegetation in flood flows.
Storage for seasonal use	High rainfall events leading to increased peak flows into impounding reservoirs can lead to overtopping. Dams may need to be operated at lower or more variable levels to mitigate against this risk, potentially reducing available storage.

	Increase in sedimentation during flood events could lead to a reduction in water storage capacity.
	Increase in turbidity during flood events could lead to water clarity and quality issues with resultant increased treatment requirements. Water may no longer be suitable for some uses at certain times of year.
Recreation and aesthetic	Increased sedimentation and debris during and following flood events - impact on recreational safety, turbidity and aesthetic value.
	Increased flows resulting in overtopping of reservoirs. For recreation and aesthetic function, impacts on downstream navigation, downstream water users (canoeists etc).
Electricity generation	Damage caused to HEP auxiliary infrastructure (power houses etc) by flooding could be very costly - damage to assets and electricity supply outage.
	Flood risk may require reduced operating levels, reducing availability or flexibility of power generation.
	Increase in water available for release during winter.
Effluent	Increased flow into impounding reservoirs increases flood risk and risk of overtopping with the resultant downstream pollution risk. Also may require lower operating levels.

3.7.3.2 Low rainfall/Drought

Prolonged dry periods or drought can also affect dam safety, the impact per dam type is summarised in Table 15 whilst the operational impacts are described in Table 16.

Table 15 Potential Impact According to the type of structure for Low Rainfall

Type of structure	Sub-type	Potential Impact
Erodible	Clay core and homogenous Clay construction	Desiccation and shrinkage of clay core and dam shoulders (clay core); desiccation of clay from surface for homogeneous dams. Leads to seepage and possible piping failure.
		Loss of vegetation cover, increasing the risk of cracking and reducing surface

		erosion protection.
		May result in lower water levels, exposing unprotected sections of the dam face to erosion.
		Decreases in summer rainfall can lead to more pronounced, more regular cycles of dam wetting and drying, potentially leading to slumping of the upstream dam face.
	HDPE liner	Low water levels and hence exposure of HDPE liner to sunlight.
	Concrete liner	Low water levels can lead to exposure of liner, increasing susceptibility to thermal cracking.
	Asphaltic concrete	Low water levels can lead to exposure of liner, increasing susceptibility to block cracking.

Table 16 Potential Impact According to the affected Dam performance for Heavy Rainfall

Operational use	Potential Impact
Storage for seasonal use	Lower rainfall will lead to lower flows, decreasing reservoir levels and less water will be available for use. Reduced yields.
	Low rainfall will increase demand for water for irrigation and environmental uses.
	For reservoirs with secondary purposes, management conflicts can occur when draw down is required for primary function (e.g. recreational use of water supply reservoirs; environmental flow releases).
	Lower water levels leading to increased concentration of pollutants, lower water quality and higher treatment requirements
Recreation and aesthetic	Drawdown exposing littoral habitat - impact on biodiversity and loss of aesthetic value.
	Low water levels may prevent certain types of recreation e.g. sailing, or cause access difficulties.

	Lower water levels leading to increased concentration of pollutants and lower water quality may reduce aesthetic value and biodiversity. May create health issues if severe.
Electricity generation	Decrease in water available for release or flush during summer.
Effluent	For impounding reservoirs this will result in lower fresh water inflows leading to increased concentration of pollutants and lower water quality.
	Lower river flows may reduce ability to abstract from and discharge to the environment.

3.7.3.3 High temperature

Prolonged periods or high temperature and heat waves can affect dam safety, the impact per dam type is summarised in Table 17, whilst the operational impacts are described in Table 18.

Table 17 Potential Impact According to the type of structure for High Temperature

Type of structure	Sub-type	Potential Impact
Erodible	Clay core and homogenous Clay construction	Increased evapotranspiration contributing to desiccation and shrinking of clay
		Increased vegetation growth on dam face, if co-incident with increased rainfall. Increased maintenance requirements.
	HDPE liner	HDPE is vulnerable to UV light; it leads to more rapid degradation of the material. High evaporation rates arising from high temperatures may lead to low water levels and increased exposure of liners to sunlight.
	Concrete liner	Increase in thermal cracking and spalling of concrete liner.
		UV damage to concrete and joint materials.
	Asphaltic concrete	Increase in block cracking of liner if asphalt dries out. May resulting in slumping and mass instability.

		Increased temperatures may result in reduced performance of current asphaltic binding mixes.
		Diurnal temperature variations can lead to longitudinal cracking.
Non-erodible	Masonry, concrete	Thermal expansion resulting in cracking and spalling.
		UV damage to concrete & masonry or jointing materials.
Spillways		Possible cracking of concrete spillways during heat waves.
Auxiliary structures		Possible cracking of concrete channels and wave walls.
		Expansion of metal elements (e.g. steel lining of tunnels, overflow valves) in excess of design tolerances.

Table 18 Potential Impact According to the affected Dam performance for High Temperature

Operational use	Potential Impact
Flood detention	Increase in vegetation growth - potential reduction in reservoir capacity and/or blocking of spillways.
Storage for seasonal use	Increase in water temperature leading to increased vegetation growth and eutrophic conditions. Increased duration and frequency of algal blooms. Reduction in water quality and increase in treatment requirements. Water may not be suitable for some purposes (e.g. environmental releases).
	Increase in evaporation of stored water, and transpiration from vegetation and soils - lower water levels in reservoirs and less available for use.
Recreation and aesthetic	Increase in pests; consider issues associated with mosquitoes in the south.
	Increase in visitor numbers in the off-peak (spring and fall) season - extended recreation and tourism season.
	Increase in vegetation growth - potential impact on aesthetic value and

	recreation potential.
	Increase in frequency of algal blooms - blue green algae can be harmful to human or pet health.
	Increased vegetation growth leading to navigation problems for some craft.
Electricity generation	Change in demand for electricity – milder winters reduce power demand, hotter summers increased demand. Opposite to seasonal water availability.
Effluent	Increased receiving water temperatures may reduce capacity of environment to accept effluent discharge and may affect ability to treat discharges.

Other factors, like high winds, can lift liners if there is no overburden in place. Risks largely associated with exposure rather than increased wind speed causes slumping and mass instability. A possible mitigation word consists in increasing overburden or weighted liners.

One of the design preventive measures is to not to build a dam in a landslide prone area. In case a landslide occurs on a nearby location and deposits rock or soil in the reservoir - overtopping might occur.

3.7.4 Remediation measures which increase resilience

Climate adaptation can be defined as the "process, or outcome of a process, that leads to a reduction in harm, risk or harm or realisation of benefits associated with climate variability and climate change"(Willows and Connell 2003). There are a wide range of adaptation measures that can be implemented but these are very dependent on the adaptive capacity of the system, i.e. how easily the system can be altered to accommodate change.

For example, an embankment may be vulnerable to erosion around crest or face structures, which could be exacerbated by cycles of wetting and drying due to climate change, leading to more significant problems such as core desiccation or even slumping failure during flood events. However, this might be simply addressed by improved crest drainage, changes in grass cutting or by excluding livestock. If the actual design or material of the embankment presents a piping risk, this may be exacerbated by increased winter rainfall and hence fill frequency, it is likely that extensive adaptation in the form of remedial capital works would be required.

As with vulnerability, the process for assessing potential adaptation measures may start by identifying the 'generic' measures that might be applied to structural resilience and performance resilience, such as;.

- Policy, planning and assessment.
- Design and construction.
- Operation and maintenance.

Final Guidance Report (2013) by the the UK Department of Environment, Food and Rural Affairs' says erodible (earthfill / rockfill) embankments are most likely to be vulnerable to climate change: increased erosion, more extreme fluctuations in water levels, changes in vegetation and prolonged drying during hot weather could combine to exploit existing weaknesses that may exist in the dam design or construction.

The form of non-erodible structures (concrete, masonry, etc.) is unlikely to be particularly vulnerable to climate change, but there are exceptions, particularly at dams where existing climatic variation is known to cause problems associated with cracking or joint movement. Overflow structures and spillways may also be vulnerable due to increasing frequency and size of flows and catchment impacts that might increase debris and vegetation. Auxiliary structures such as valves or draw off towers may be vulnerable to similar effects and can be prone to other factors such as siltation or heat induced expansion.

Figure 102 Joint and Cracking Maintenance83

Figure 103 Valves maintenance84

[83] https://www.dvidshub.net/image/1753070/lock-and-dam-5a-winter-maintenance-project#.VWQfFkZRRpU
http://www.defensemedianetwork.com/stories/the-army-corps-of-engineers-civil-works-program/

Figure 104 Maintenance operations (debris and vegetation removal and sedimentation dredging)[85]

Figure 105 Spillway maintenance[86]

Dam performance can be affected in a variety of ways, including the more 'obvious' impacts such as changes in hydrology or water quality, and less apparent issues such as increasing water level fluctuation leading to a deterioration in marginal vegetation conditions and hence bankside fishery

[84] http://www.defensemedianetwork.com/stories/usaces-national-asset-management-approach-improving-organizational-decision-making/

[85] http://i.ytimg.com/vi/v0DjxMoSM58/maxresdefault.jpghttp://www.dredgingtoday.com/2013/03/08/video-geluk-dredging-dredging-in-dams-austria/

[86] http://www.kleinschmidtgroup.com/service-areas/hydroelectric-engineering-hydropower-engineering-consultants/dam-and-spillway-engineering/rehabilitation-design/

http://siouxcityjournal.com/news/local/a1/corps-begins-work-on-gavins-point-spillway/article_cc50c343-2d30-5160-83c7-cbbaadae6230.html functions. Such issues need to be evaluated through a combination of approaches, ranging from predictive modelling (for hydrology/yield or water quality), to trend analysis or simple analysis of change factors by operators that are sufficiently familiar with the reservoir and catchment.

4 Summary and Conclusions

According to the European Commission report Adapting Infrastructure to climate change (2013) the impact of weather stresses represents 30% to 50% of current road maintenance costs in Europe. Major failure of elements of infrastructure as a result of weather impacts is increasing. The report "Impacts of Europe's changing climate – 2008 indicator-based assessment" by the EEA and JCR, identifies the need to limit deterioration effects from adverse weather conditions (e.g. prolonged precipitation, heat stress, freeze-thaw cycle) and damaging consequences in case of extreme events (i.e. storms and floods) as a key factor influencing construction designs.

This report considers the effect of climate change on major infrastructure assets in the surface transport and energy domains. By first considering typical effects across a range of infrastructure, a set of likely hazards affecting elements of infrastructure were identified. Whilst some infrastructure elements, e.g. bridges and slopes are affected by multiple weather hazards, others such as tunnels and dams are primarily affected by one hazard.

Remediation measures which increase the resilience of elements are presented. The methods can be broadly classified as (i) design and construction related (ii) retrofitted solutions and (iii) indirect methods. Given that the current infrastructure network is a significant asset, and portions of the network are very old (e.g. parts of the European rail network are more than 150 years old) a focus was given to increasing the resilience of existing infrastructure. In addition methods which could be implemented directly by an infrastructure manager, e.g. the provision of rock protection netting rather than indirect approaches, for example, reducing the impact of flooding on bridge scour by introducing a regional flood protection system were favoured. In summary a range of effective methods of increasing resilience are available to infrastructure managers. The choice of which solution to adopt will depend primarily on available budget and the risk rating for the element. The remedial measures described in this report will be used to inform later work on technical impact matrices performed in Work Package 7 of the RAIN project. This type of approach will allow rational decisions to be made on optimal expenditure in maintenance and renewal. The Technical Impact Matrix approach which will be presented in Task 7.2 will rank remediation measures with regards to cost, effectiveness, environmental impact, risk to humans and financial loss.

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