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# Re-Gen
# Risk Assessment of Ageing Infrastructure

# Report of Critical Infrastructure Elements

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Roughan & O Donovan Innovative Solutions (ROD-IS), Ireland
Gavin and Doherty Geosolutions Ltd. (GDG), Ireland
Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia
Institut Français des Sciences et Technologies des Transports de L'amenagement et des Reseaux (IFSTTAR), France
Rambøll Denmark A/S, Denmark
Delft University of Technology, Netherlands

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**Author of this deliverable**:
Pei-Hui Lin, TU Delft, Netherlands
Pieter van Gelder, TU Delft, Netherlands
Yamin Huang, TU Delft, Netherlands
Laobing Zhang, TU Delft, Netherlands
Kim Obel Nielsen, Rambøll Denmark A/S, Denmark
Claus Pedersen, Rambøll Denmark A/S, Denmark
Paul Doherty, Gavin and Doherty Geosolutions Ltd., Ireland
Matilda Djidara, Gavin and Doherty Geosolutions Ltd., Ireland

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# Executive summary

The effects of climate change include new precipitation patterns, increasing temperature ranges, varying wind regimes and an increasing number of extreme weather events. The impacts of these climatic changes can have drastic consequences for the effected elements of the road infrastructure network. This report reviews the available literature with respect to the impact of climate change on specific structures including bridges, retaining walls and earthwork assets (slopes).

A detailed review of the published literature was undertaken which identified a dearth of available relevant information. This included limited information on categorizing the importance of road infrastructure with respect to the criticality of various elements exposed to climate change effects (e.g. maximum network disruption, maximum maintenance expenditure, perceived maximum risk to operation, etc.).

The most likely failure mechanisms for different road infrastructure elements are addressed in this report. General information on structural, geotechnical and functional failure modes are considered in order to assess the criticality of bridges, steep slopes and retaining walls subject to climate change. The potential impact of climate change on the future condition of various infrastructure elements are also addressed with respect to the geographical location of the infrastructure. The degradation of infrastructure located in each of the following terrain is considered: (i) Seaside locations; (ii) Adjacent to Rivers; and (iii) Mountainous areas.

General information on structural failures and functional failures of retaining walls are provided. According to the IPCC climate change predictions, it is expected that retaining walls will be exposed to higher carbon concentrations, changes in temperature, humidity and overall air pollution, which will trigger degradation mechanisms such as chloride induced corrosion, carbonation, sulphate attack, alkali-aggregate, alkali-silica and alkali-carbonate reaction. These degradation processes, accelerated by climate change, will reduce the structural lifetime of these assets.

Climate change induced changes in rainfall intensity and in particular increasing volumes of precipitation over short durations are of most critical concern for slope infrastructure, where the increasing rainfall patterns will reduce matric suction within the soil body and thereby reduce the effective stress conditions. This in turn will lead to an overall reduction in the slope stability during rainfall events as the slope saturation increases and the margin of safety reduces. The types of slope failures that may impact on road infrastructure could include both local slips and global landslide events depending on the volume of material mobilised. The failure mechanisms for both local slope failures and landslides are similar and both can have dramatic impacts on the road operability, with the remedial solutions often requiring road closures while significant repairs works are undertaken.

The main deterioration mechanisms for concrete bridges are seen to be corrosion, freeze and alkali-silica reactions; whereas for steel bridges corrosion and fatigue are the dominant mechanisms. In terms of climate change effects, corrosion is the primary degradation mechanism affected. This report summarises the various failure modes for bridge structures subjected to changing climatic conditions.

# 1 Introduction

The objective of this deliverable was to review the available literature from previous research projects and to identify those areas where information is lacking with respect to the failure modes of various infrastructure elements that may be sensitive to climate change effects.

This desk study exercise involved reviewing the available data from previous research projects in order to identify the asset classes of road infrastructure (concrete bridges, steel bridges, slope assets and retaining walls) that cause maximum network disruption, maximum maintenance expenditure and perceived maximum risk to operation considering climate change. It was hoped that the literature would be able to provide an indication of which infrastructure elements were most critically influenced by climate change effects.

A list of targeted projects and published papers were identified at the outset, which are listed below and while this information was reviewed in detail, this desk study exercise yielded limited information with respect to the objectives surrounding the identification of critical infrastructure elements that are sensitive to climate change:

- CEDR project RIMAROCC
- CEDR project ROADAPT
- GB Department of Transport “A review of the resilience of the transport network to extreme weather events”
- Alexander Fekete (Federal Office of Civil Protection and Disaster Assistance, 53008 Bonn, Germany) “Common Criteria for the Assessment of Critical Infrastructures”
- CE DELFT & partners, project IMPACT, commissioned by European Commission- “Road Infrastructure cost and revenue in Europe”
- ERF-European road statistics 2011
- ERF-European road statistics 2012
- CEDR Trans-European road network, TEN-T (Roads): 2011 performance report

The following sections consider (i) retaining walls, (ii) slope assets and (iii) bridges separately with a view to looking at the relevant failure modes for each type of asset.

# 2 Retaining walls

## *2.1 Introduction*

Retaining walls are required due to changes in topography where a physical structure is needed to resist the lateral earth pressure of the soil generated from the higher ground elevation on one side of the wall. Retaining walls are a common feature of road networks throughout Europe and are particularly common where the landscape involves significant variations in topography. As a result, it may be expected that mountainous countries may have a larger inventory of retaining wall assets than comparatively flat countries.

The importance of ensuring the stability of retaining wall assets and the implications of their failure is well demonstrated by a tragic accident happened in Austria in March of 2012 during the snowmelt. This accident occurred on the Brenner motorway heading toward Italy where a very sudden failure of a 6m high concrete retaining wall impacted a truck travelling in the adjacent carriageway, crushing the vehicle and killing the driver. The causes of this failure were not revealed in the media, but as can be seen from the photo the melting snow carried debris increased the loading behind the wall. A significant structural failure of the concrete stem is visible in the photo below, however changes to the pore pressure regime may have also exacerbated the loading conditions and the exact sequence of the failure is not certain, although the weather events are likely to have played a significant role in the overturning failure.

**Figure 2.1 Wall failure in Austria (OE24, 2012)**

Retaining wall failures can occur either due to failure within the wall itself or due to the changes in the conditions in the retained soil, which may lead to increased loading. Climate change effects which induce different degradation mechanisms for different geographical locations will be discussed in the following text.

## 2.2 Infrastructure elements

### 2.2.1 The wall structure

Retaining structures can be classified as follows according to the type of the material:

**Table 2.1 Retaining structures classification**

<table>
<tr><th colspan="3">Reinforced Concrete</th></tr>
<tr><td>Either precast or cast in situ concrete can be used to construct a retaining wall. Concrete solutions have the advantage of providing a variety of shapes and different structural systems and are often used in combination with other systems (i.e. with anchors).<br>Most concrete walls resist the applied forces through gravity forces.</td><td></td><td></td></tr>
<tr><th colspan="3">Brick and Stone Masonry</th></tr>
<tr><td colspan="2">When considering a complete road infrastructure network, it is important to differentiate between national routes and motorways and secondary or more rural routes. The motorway network are typically more modern and will contain a larger number of concrete retaining wall assets than compared to the secondary routes which will primarily contain older wall assets and as such will have a high proportion of masonry structures. One of the failure mechanisms associated with masonry retaining walls is that the binding mortar will wash out during the lifespan of the structure.<br><br>Similar to most concrete walls, brick and masonry retaining structure tend to resist the applied forces through gravity action.</td><td></td></tr>
</table>

| Reinforced Soil Walls | |
|---|---|
| Reinforced Soil has gained significant traction over the past two decades as the development of this technology has allowed sloped retaining walls to be constructed at steeper gradients than was previously possible without a conventional gravity type wall. The technologies available on the market allow steep gradients. By introducing vegetation or concrete facing, as presented in the adjacent photo, a more aesthetically pleasing finish can be achieved in comparison to standard concrete construction. The terminology for such slopes considers that reinforced soil with facing angle up to 70º are considered to be **reinforced slopes**, where angles beyond 70º are considered to be **reinforced soil walls**. Both types of structure typically resist the overturning forces through a series of facing elements that are connected to tension members which project backwards into the soil mass and therefore utilise the dead-weight of the soil block as a resisting gravity mass. |  |
| Gabions | |
| Gabion walls, are constructed out of wire cages (or boxes) filled with rock. They have widespread appeal as they can be constructed relatively cheaply due to the wide availability and low cost of the required materials. The construction time can be also quite quick as there is no concrete curing time required. Gabion walls also act as gravity walls with the dead-weight of the baskets providing sufficient resistance to avoid overturning. |  |
| Steel Sheet Pile Walls | |
| Sheet pile walls are constructed by driving steel piles into the ground with the top of the piles projecting sufficient distance to retain a body of earth on one side of the wall. Alternatively sheet piles are often used to facilitate a vertical excavation to one side of the wall. This form of construction is used both for temporary constructions during excavation works and for permanent support structures due to their low cost and simple installation. The sheet piles resist the applied earth pressures through mobilised active and passive forces within the embedded portion and the above ground portion acting as a simple cantilever. presented in the photo. |  |

From a structural point of view (**Figure** ) there are several types of wall, which have been classified below depending on how they resist the applied loads:

**Gravity Walls** rely on their weight to retain the material behind them and achieve stability. Excessive weight keeps the walls stable when subjected to sliding and rotational forces. They can be constructed out of stone, reinforced concrete, or blockwork. These types of walls are mostly suitable for retained heights up to 3 m but subject to proper engineering there is no real upper limit on the wall height.

**Piled Walls** are much thinner, either steel profiles or in situ/precast concrete elements with various cross sections are used. Piled walls include sheet pile walls, secant, king post and contiguous sections. Sheet pile walls involve driving interlocking sheets into the ground, which can be sealed using a rubber compound poured into the clutches at the joints. Secant walls involve boring and casting concrete circular piles in an interlocking sequence of female piles (containing soft concrete and installed first) and subsequent male piles (containing hard concrete and bored through the female piles). Contiguous piles are similar to secant walls although there is a gap between the piles and therefore the wall is permeable. All of the walls described above can act in isolation resisting the applied stresses by mobilisation of active and passive earth pressures in the ground.

**Cantilever retaining walls** consists of a stem and foundation (with a heel). This type of wall is quite efficient as it takes advantage of the retained soil to increase the wall resistance relative to the amount of concrete material used to construct the wall. The stem of the wall is constructed as an upstand on the foundation which projects into the soil mass, hence the foundation slab is loaded by the backfill as well, and together with the surcharge acts beneficially in prevention of overturning and sliding.

**Anchored walls** are typically piled walls, used where the retained height is such that the wall is at the limit of what a pile can resist and therefore additional load carrying capacity is mobilised by the installation of anchors or tie-backs. Anchors increase the stiffness of the wall system and help minimise the deflections. Anchors may be passive or active depending on whether a pre-stressing force has been applied.

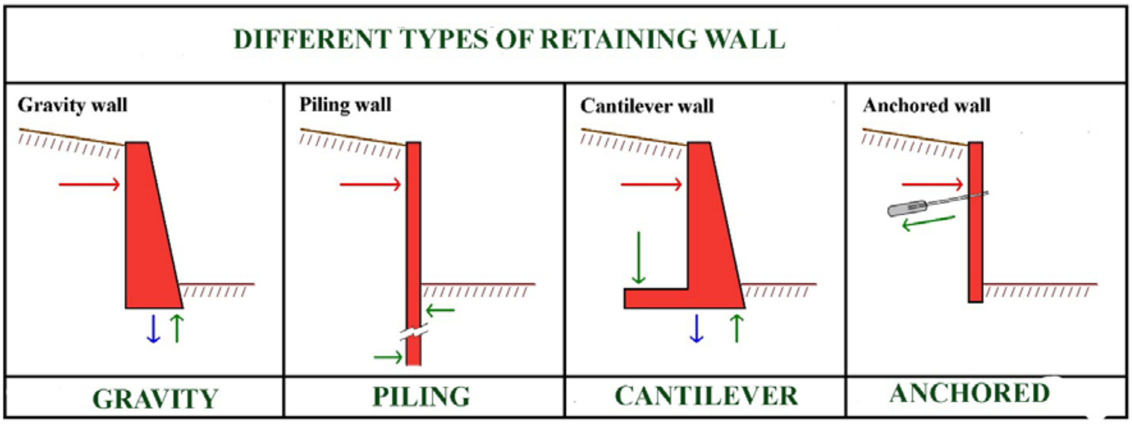



**Figure 2.2 Different types of retaining wall**

The following table correlates the material type and the structural type of the wall.

**Table 2.2 Structural types and material types in relation to one another**

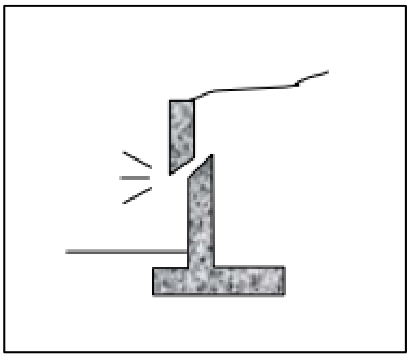
| Material Type / Structural type | Concrete/ Reinforced Concrete Walls | Masonry | Reinforced Soil Walls | Gabions | Steel Sheet Piles |
|---|---|---|---|---|---|
| Gravity | ✓ | ✓ | ✓ | ✓ | n.a. |
| Piling | ✓ [a] | n.a. | n.a. | n.a. | ✓ |
| Cantilever | ✓ | n.a. | n.a. | n.a. | n.a. |
| Anchored | ✓ | ✓ [b] | ✓ [c] | n.a. | ✓ |

[a] Concrete Piles
[b] In case of remediation works on old masonry retaining walls
[c] Soil Nails

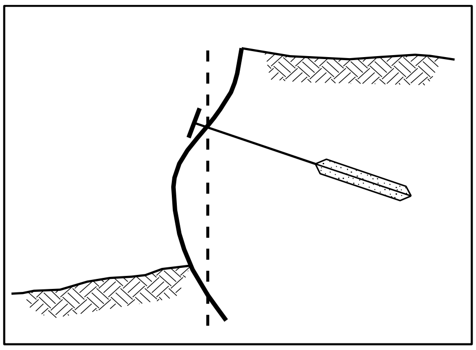
## *2.2.2 The failure modes*

The failure modes considered for retaining walls cover both structural and functional failures. Structural failures are those which occur in the wall segment (failure in the reinforced concrete or steel sheet pile walls) and the functional failure happens due to interaction with the soil (within the retained portion of the ground).

**(1) Stem failure:** (a) the concrete can deteriorate by weathering, caused by e.g. freeze-thaw effects, and corrosion of reinforcement can cause cracking and spalling of the concrete. The corrosion of reinforcement can be induced by carbonation, chloride penetration and/or combinations of both. Failure mode within a pile wall (b) can be triggered by the above stated deterioration mechanism for reinforced concrete or simple corrosion when it comes to sheet pile walls.



(a)



(b)

**Figure 2.3 Failure within the stem of the retaining wall**

**(2) Anchor Failure** (**Figure 2.4**): Increased loading can occur due to additional surcharges, such as snow loads or increased water pressures due to poor drainage conditions. For an unanchored wall this would typically lead to increased deflections and potential serviceability problems prior to collapse. However, in the case of anchored walls the increased stiffness of the system may result in a brittle failure, caused by either sudden pull-out of the anchor as the grout/ground bond fails or alternatively overloading of the tendon causing a structural failure of the steel within the anchor.

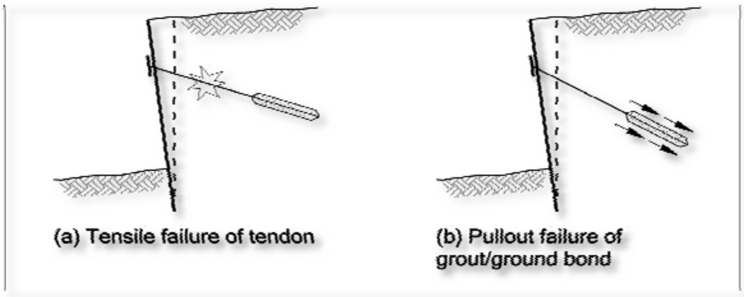



**Figure 2.4 Failure within the anchor system**

**(3) Drainage Failure** refers to cases where the wall may be designed as a permeable solution (typically with weep holes) and is therefore not designed to withstand any hydrostatic water pressure behind the wall, however in the case where the drainage is not effective the wall may experience a significantly higher load due to the requirement to support the water pressure. Typically this mode of failure is exacerbated by poor design of the drainage system or poor construction details that do not allow effective maintenance.

**(4) Geotechnical Failure** means the failure due to the soil feature changes and leads to the failure of the whole retaining wall system. The specific failure modes are shown as follow:

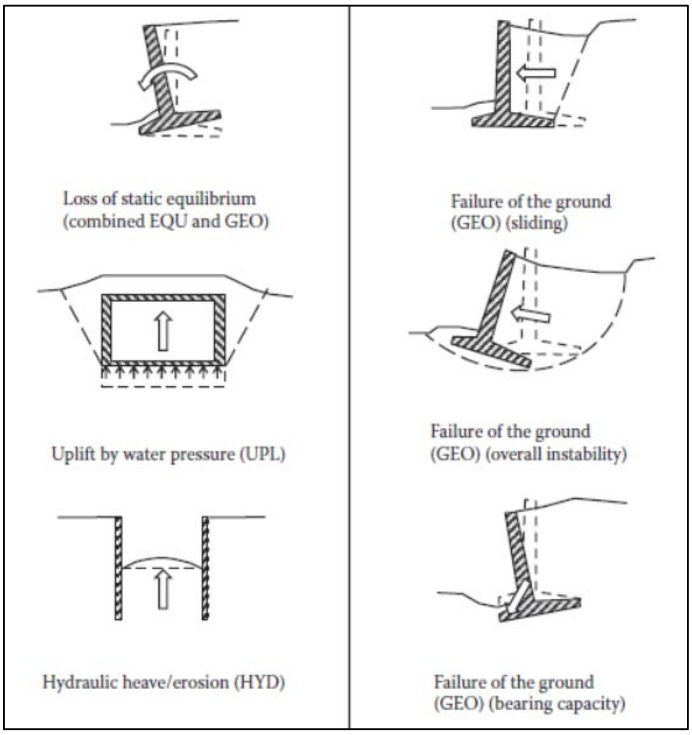



**Figure 2.5 The failure due to the soil feature changes (Clayton, 2014)**

(i) Overturning: This manifests as a rotational failure of the wall, typically where the wall rotates around the toe due to the overturning moment exceeding the stabilising moment of the resisting forces.

(ii) Sliding: This mode of failure occurs due to insufficient friction between the base of the footing and the soil in contact with the foundation. This manifests as a translation of the wall away from the original position and typically can be identified at an early stage by tension cracking observed at the ground surface due to separation of the wall and backfill material.

(iii) Uplift by water pressure: An imbalance between the hydrostatic buoyancy forces acting on the structure and the resisting gravity forces can result in a loss of equilibrium causing the structure to heave upwards.

(iv) Overall instability: The global stability takes into account the stability of the soil above and below the retaining structure. It is important to note that global instability can be triggered by local geological conditions and preferential slip circles in the underlying soil.

(v) Hydraulic heave/erosion: This failure mode refers to internal erosion (piping) of the soil due to the hydraulic forces caused by variable hydraulic gradients. As a result, the effective stresses within the soil body are reduced to zero and during piping failure, the strength of the ground has minimal resistance against instability.

(vi) Bearing capacity: This mode of failure refers to a bearing capacity failure where the supporting soil beneath the foundation cannot withstand the applied stresses from the wall and as a result shear failure planes are created in the soil mass leading to an overall failure of the wall system. To minimise the risk of footing failure loose deposits or soft soil are often excavated prior to wall construction and the foundation soil is then built directly on top of a replaced granular layer. The impact of climate change on this mode of failure is limited to cohesive soils subject to shrinking/swelling in response to wetting and drying cycles and in this regard changes to the seasonal fluctuations in soil moisture content could have a significant impact on the stability of the foundation.

The behaviour of the retained soil (backfill) depends on its composition. The backfill can either be cohesive (clay) or non-cohesive (sand and gravel). Usually, cohesive backfills have lower shear strengths, they also have poor drainage and the potential for the development of water pressure. Clay materials are prone to creep deformations which lead to higher earth pressures. Non-cohesive materials, allow free draining and have better overall performance.

### 2.2.3 Climate Change Effect Impact

The 2007 IPCC report included a number of major predictions for Europe, which are outlined below:

- The British Isles alongside the Benelux countries and Northwest of France will be affected by the increased coastal erosion and flooding. The coastal impacts, together with increased winter storms and winds, will have a negative impact on the transport network.
- The mountainous terrain throughout the Europe, e.g. Scandinavia, Alps or Dinarides will deal with the melting of glaciers, thus reducing snow cover and increasing rock falls. Scandinavia and the Baltic will experience cases of waterlogging, higher risk of winter storms, coastal flooding and erosion.
- Most of Continental Europe will also be affected by the increased events of floods in summertime and the Mediterranean will experience higher heatwaves in the summer period, reduction of hydropower and increase of salinity.

As stated in CEDR’s report “Adaptation to climate change” we can form two regions: (I) the Northern and Eastern Europe and (II) Southern, Western and Central Europe. The former will be impacted by wetter winters and the latter by dryer summers (CEDR, 2012).

The deterioration mechanism for reinforced concrete and steel are presented in Table 2.3 below:

**Table 2.3 Possible deterioration mechanism for reinforced concrete and steel elements**

| | DETERIORATION MECHANISM |
|---|---|
| Reinforced Concrete | Chloride-induced corrosion |
| | Carbonation |
| | Sulphate attack |
| | Alkali-aggregate reaction |
| | Alkali-silica reaction |
| | Alkali-carbonate reaction |
| | Freeze-thaw cycles |
| Steel | Corrosion |
| | Degradation of protective coating |
| | Fatigue |

Depending on the geographic position of the retaining wall, the possibility of the deterioration mechanism can either increase or decrease and be more or less affected by changes in climate conditions. The following section describes how the climatic threats for retaining walls vary with respect to the location type.

## *2.3 Location types*

According to climate change predictions (IPCC, 2007) higher carbon concentrations, changes in temperature, humidity and overall air pollution (regardless of geographical location), are expected. All of these climatic factors are potential triggers for many degradation mechanisms such as those stated in table 2.3.

Tables 2.5 - 2.7 discuss the likelihood of a negative effect in relation to the various failure scenarios identified in Table 2.4.

**Table 2.4 Possible failure scenarios for different geographical locations**

| Natural Surroundings/ Geographical Area | Possible Climate Change Scenario | Possible Impact on the Retaining Wall |
|---|---|---|
| Seaside | (a) Change in the Salinity<br>(b) Sea Level Rise | (a) With the increase in salinity, concrete elements will be exposed to higher concentrations of chlorides and the response time for the chloride ingress will be shortened (Chloride induced corrosion).<br>(b) As sea level rises, there will be an extension of the splash zone, with more structural elements exposed to salt water, and therefore the likelihood for more elements to be negatively affected by chloride induced attack. |
| Riverside | (c) Higher Frequency of Flood events due to change in the precipitation patterns | (c) Local and Global Stability of retaining walls may be affected by the flood waters, possible erosion of the soil and damage to the drainage system. This could result in either geotechnical or structural failure mechanisms. |
| Mountains | (d) Increased precipitation<br>(e) Changing Temperatures leading to Glacial Retreat/ Snow Melting<br>(f) Freeze-Thaw Cycles | (d) Global stability of the Wall is affected by increased rainfall intensity and snows which could negatively impact on the pore water pressure conditions in the retained soil.<br>(e) Higher risks of landslides and rockfalls.<br>(f) Deterioration of concrete. |

## Table 2.5 Likelihood of an event for seaside environment

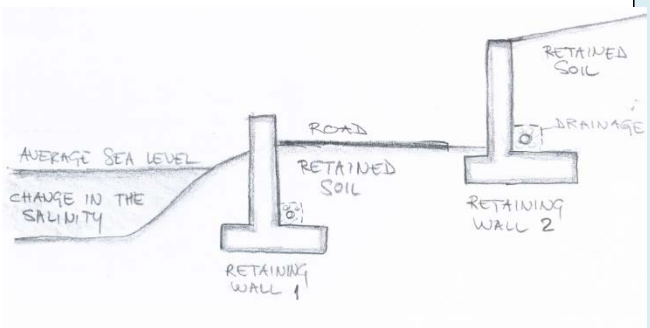
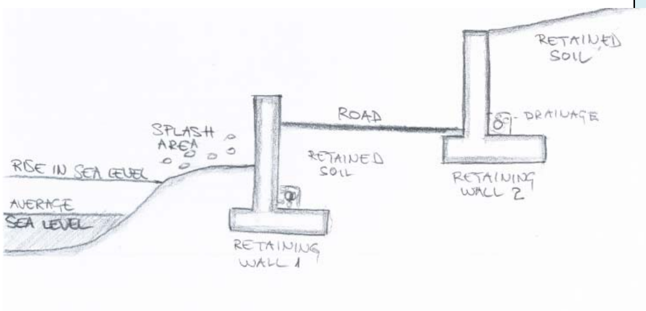
| Seaside Environment | | | |
|---|---|---|---|
| Potential Threat | Illustrative description | Likelihood of an event for retaining wall 1 | Likelihood of an event for retaining wall 2 |
| Change in the Salinity |   | High | Med |
| Increase of the Sea Level (Increase of Splash Area) |   | High | Med |

**Table 2.6 Likelihood of an event for riverside environment**

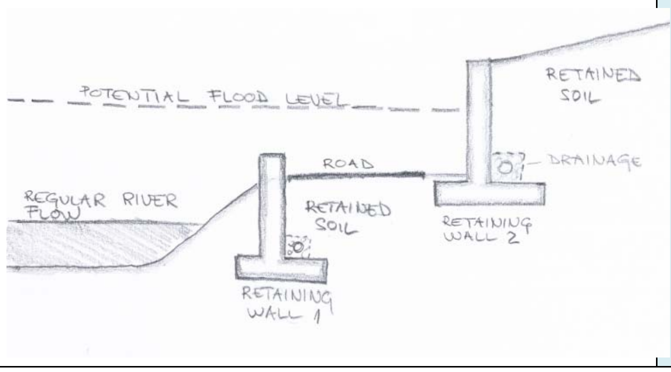
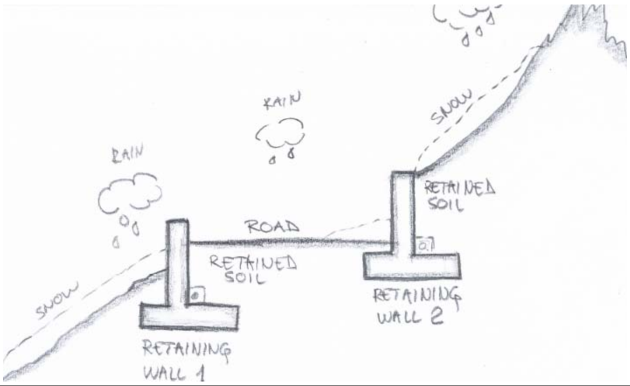
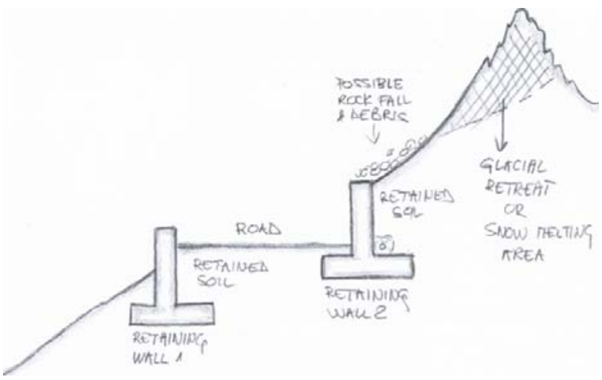
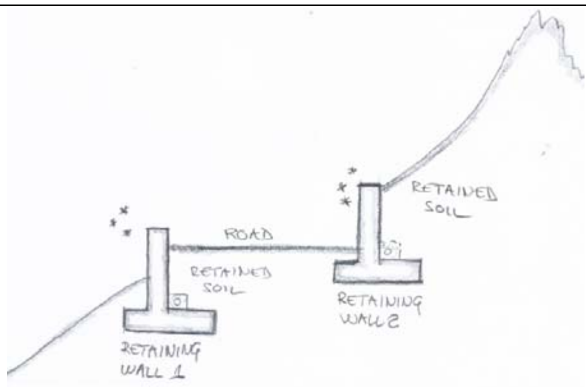
| Riverside Environment | | | |
|---|---|---|---|
| Potential Threat | Illustrative description | Likelihood of an event for retaining wall 1 | Likelihood of an event for retaining wall 2 |
| Flood |  | High | Medium |

**Table 2.7 Likelihood of an event for mountainous environment**

<table>
<tr><td colspan="4">Mountainous Environment</td></tr>
<tr><td>Potential Threat</td><td>Illustrative description</td><td>Likelihood of an event for retaining wall 1</td><td>Likelihood of an event for retaining wall 2</td></tr>
<tr><td>Increased Precipitation (Snow and Rain)</td><td></td><td>High</td><td>High</td></tr>
<tr><td>Glacial Retreat / Snow Melting</td><td></td><td>Medium</td><td>High</td></tr>
<tr><td>Freeze Thaw</td><td></td><td>High</td><td>High</td></tr>
</table>

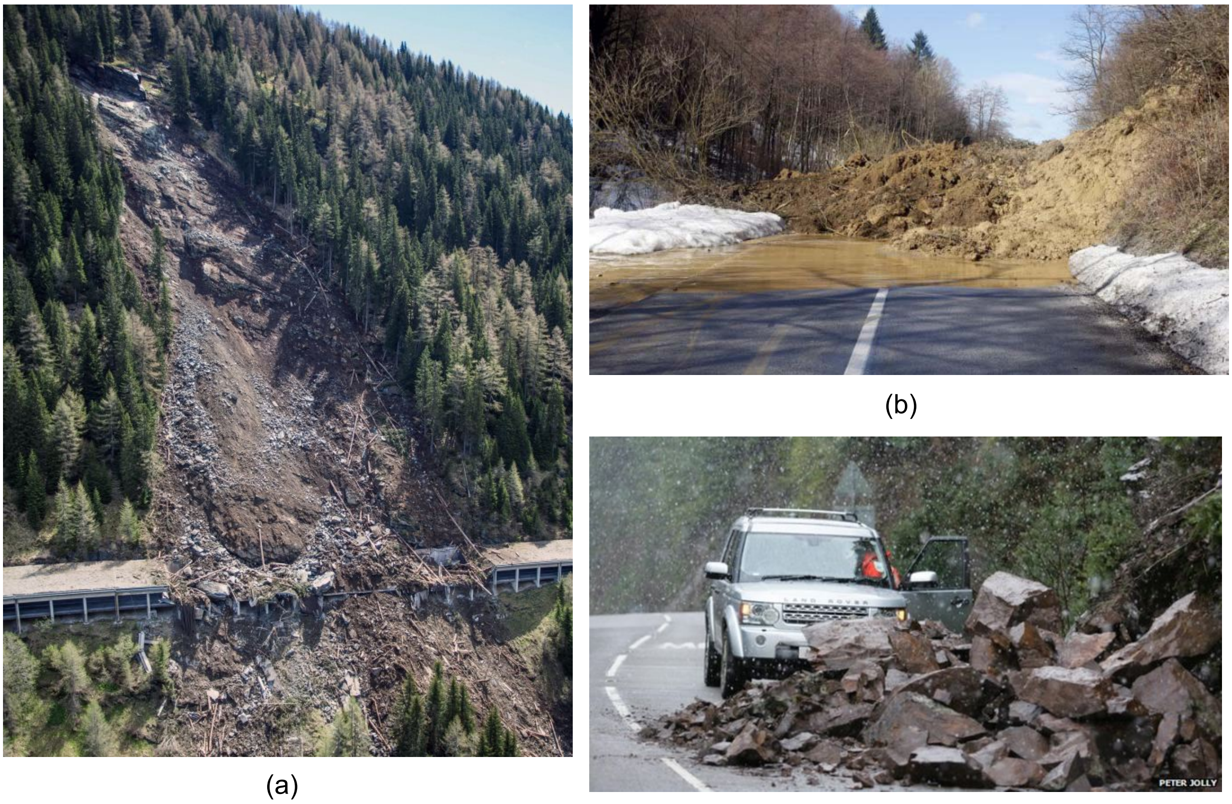
## 2.4 Summary

Retaining walls are designed to resist the lateral earth pressure which comes from a desired change in ground elevation that exceeds the angle of repose of the retained soil. Potential failure modes can be structural or geotechnical, with structural failures occurring within the wall segment (failure in reinforced concrete or steel sheet pile walls) and the geotechnical failure modes being driven by interactions with the soil (within the retained portion of the ground). The impact of climate change on retaining walls were considered with specific reference to those climatic factors identified by the IPCC to be significant. For example, retaining wall structures are predicted to be exposed to higher carbon concentrations, changes in temperature, humidity and overall air pollution (regardless of the geographical location), which will trigger many degradation mechanisms such as e.g. chloride induced corrosion, carbonation, sulphate attack, alkali-aggregate, alkali-silica and alkali-carbonate reaction. In addition, for retaining walls located in one of the more critical geographical areas (sea side, river side and the mountainous areas), the likelihood of a negative impact increases.

# 3 Slopes

## *3.1 Introduction*

Natural slopes and manmade cuttings and embankments typically exist in a state of equilibrium where the gravity forces driving the slope material downhill are resisted by the shear strength of the soil/rock material. However, once this delicate state of equilibrium is subjected to an unbalancing force, then the results can be catastrophic. These forces can be generated by external loads placed on the slopes or alternatively by changes to the porewater regime, which could be triggered by increased rainfall or drainage issues. In recent years, the road infrastructure network across Europe has experienced several slope failure events as captured by the images below, which include (a) an interface rock-mudslide in Austria in May 2013, (b) a soil landslip on a local road in Croatia in March 2013 and (c) a rock fall in Scotland in March 2015 (Figure ). These events have all occurred in early spring time, immediately after periods of heavy snow and rainfall in mountainous and hilly areas.




(a) (b) (c)

**Figure 3.1 Rock-Mudslide in Eastern Tirol in Austria (Dailymail, 2013), (b) Landslip in Visnjica Croatia (Vecernji, 2013), (c) Rock fall in Scotland on A82 (BBC, 2015)**

In order to help identify which slopes are more critical to the road infrastructure, it is necessary to understand the failure mechanisms and to determine the critical trigger factors such as e.g. change in precipitation, freeze-thaw effect or changes in vegetation. The potential for slope failures with respect to the geographical location have also been considered in a similar fashion to the retaining wall asset discussed in the previous section.

Slopes are either manmade or naturally formed. Wherever the ground does not have a level surface with a zero gradient, there are forces with the tendency to cause the movement of the soil body from the higher to the lower point. The main factors influencing the slope stability are the gravitational force and the water pressure, acting together, producing shear stresses throughout the slope body, and unless the shearing resistance is higher than the stress a failure will occur. The resistance is highly dependent on the nature of the slope material and the local geological conditions.

Local slope failures and landslides can be distinguished from each other based on the volume of the mobilised soil. However, both local slope failures and landslides have similar mechanisms and can both negatively impact the road infrastructure. Landslides affect greater areas, bringing devastation to houses, roads, energy lines etc., in contrast to local slope failures, which only affect the isolated cutting/embankment body and the adjacent road. Both local slope failures and landslides have the same failure mechanisms, either due to increased stress or decrease in strength (imbalance in the equilibrium). In the subsequent sections, both local slope failures and landslides will be considered together.

## *3.2 Slopes as Infrastructure elements*

Slopes are commonly occurring road infrastructure elements which provide the link between the designed road surface and the natural surroundings. Even engineered slopes are made out of natural material, which leaves a degree of uncertainty in relation to the exact parameters and the performance, so in addition to robust engineering, monitoring and maintenance are crucial to the management of these infrastructure elements.

**Table** provides different classifications of slopes.

**Table 3.1 Different types of slopes**

| Slope classification | | |
|---|---|---|
| According to the origin | Natural | Existing slopes formed by natural forces. The natural topography / landscape is incorporated into the transport infrastructure network. |
| | Engineered Slopes (Manmade) | **Embankments and Cuttings –** These elements are usually designed as a part of road infrastructure in order to accommodate the horizontal and vertical alignment, and are accompanied by structural elements (i.e. anchors, geo-mesh) in order to provide reinforcing with an aim to achieve stability and the required gradient. The gradient of such slopes are normally specified by national standards (for example cut soil slopes are not to exceed 2H:1V). |
| According to the ground material type | Rock Slopes | Mostly slopes cut into the existing rock. The stability of such slopes is highly dependent on the competency of the rock and geological factors such as the jointing pattern plays a crucial role in this regard. |
| | Soil Slopes | These can be engineered slopes, either cut into the natural ground, or embankment constructed from fill material, or alternatively soil slopes can be natural slopes from the existing topography. |
| According to the type of construction | Cut | As previously mentioned, Engineered Slopes are either Cut or Fill, depending on the position of the new road alignment in relation to the existing terrain. For major road schemes the requirement to maintain a material balance, in combination with the rules surrounding the horizontal and vertical alignment, drive the decision to excavate a slope or construct an embankment. |
| | Fill | |
| According to vegetation type | Vegetated | Vegetation can have a significant impact on slope stability, locally lowering the water table and increasing the effective strength of the soil material. |
| | Un-vegetated | |

The following images represent various different types of slopes: (a) Engineered Soil Cutting with structural reinforcement; (b) Natural Rock Slope (cutting/embankment); (c) Engineered Soil Embankment (d) Engineered Road Rock Cutting with Structural Reinforcement (being installed)

(a)

(b)

(c)

(d)

**Figure 3.2 Different types of road slopes**

### *3.2.1 Slope Stability (Landslides and Local Slope Failures)*

Local slope failures and landslides can cause havoc and disruption when they impact the road network. Landslides are triggered by various factors such as hazardous events (i.e. earthquakes), climate change effects (i.e. changes in precipitation patterns), or human activity, hence causing damage to roads, houses, railways, dam failures and human fatalities. Some of the contributing factors are of geological, geotechnical, and hydrogeological nature in combination with land use/land cover. The triggers can be grouped in two separate groups depending on the trigger time; instantaneous and gradual. An extreme hazard event can trigger a failure in a matter of hours, where in contrast the change in precipitation patterns will trigger the failure gradually. Local failure of engineered slopes, though seldom occurring, happens mostly due to local geological discontinuities, poor design or inadequate workmanship.

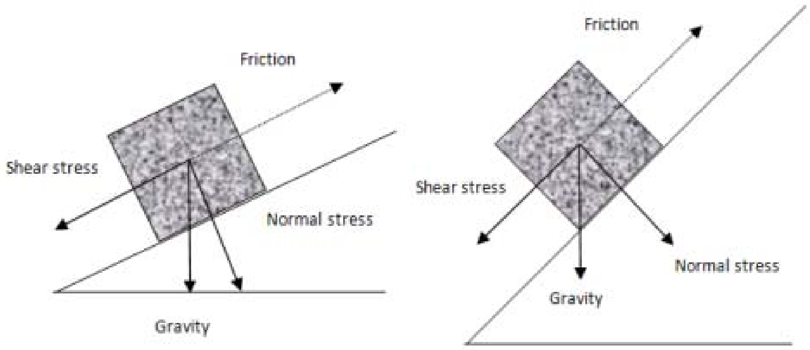



**Figure 3.3 Sliding mechanism**

Figure 3.3 demonstrates the force equilibrium that controls the sliding mechanism that underpins most slope failures. With the increase of the slope angle, the tangential stress increases which results in increase of the shear stress and a decrease in the normal stress, with a resultant decrease in the frictional resistance and stability of the soil mass (or block in the case of Figure 3.3).

The type of landslide movement depends on many factors including slope gradient, material type, hydrological conditions and vegetation coverage. Landslides and slope failures come in various shapes and sizes. They are described from minor to major, both in regards to affected landslide area and the devastation they cause. The following table (**Table** ) summarises the landslide types of movements by the British Geological Survey classification (BGS).

**Table 3.2 Landslide types according to BGS**

| Type of Movement | Description |
|---|---|
| Flow | Slow to rapid mass movement in saturated or dry materials which advance by viscous flow, usually following an initial sliding movement. Some flows may be bounded by basal and marginal shear, surfaces but the dominant movement of the displaced mass is by flowage. |
| Rotational Slide | Or slumps where masses slide outwards on one or more concave-upward failure surfaces. |
| Planar Slide | Or a translational slide, where movements occur along planar failure surfaces, running more or less parallel to the slope. |
| Fall | Mass detached from steep slope/cliff along surface with little or no shear displacement, descends mostly through the air by free fall, bouncing or rolling. |
| Topple | Movement of rock, debris or earth masses by forward rotation about a pivot point. |
| Spread | Involve the fracturing and lateral extension of coherent rock or soil masses due to plastic flow or liquefaction of subjacent material. |
| Complex | Slides involving one of the main types of movement followed by two or more of the other main movement types in combination. |

The following image, Figure 3.4, gives an illustrative description of different types of movements for rock, debris and earth.

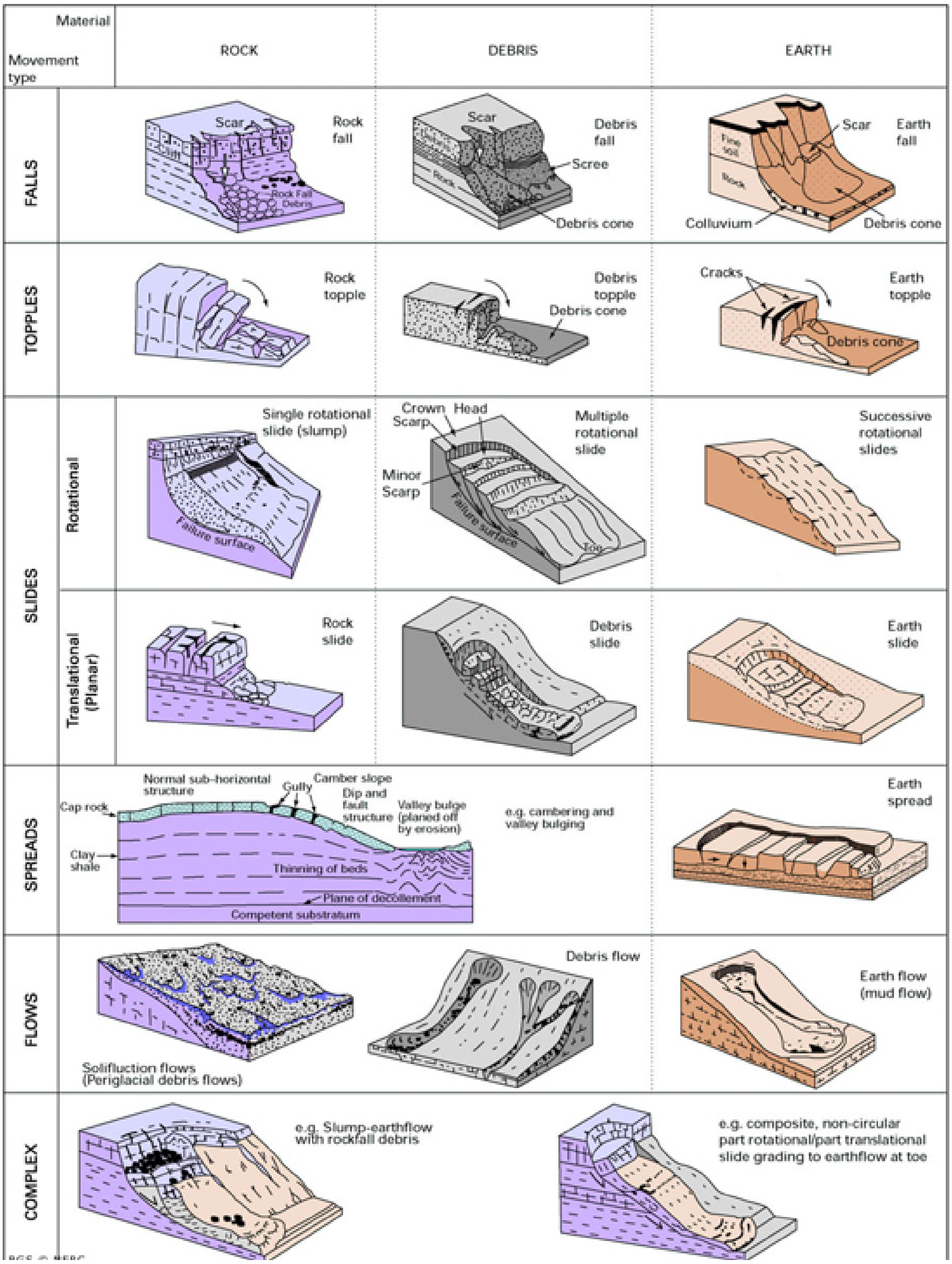



**Figure 3.4 Various types of landslides (BGS, 2015)**

The Geological Survey Ireland landslide report “Landslides in Ireland” explains the following terms:

**(1)** FLOWS can occur in bedrock but they are extremely slow and occur in areas of high (geographical) relief. Flows in unconsolidated materials are much more obvious. In terms of speed, flows can range from slow to very fast, and in terms of moisture content, can range from saturated to dry. However, the effect of water is important in initiating flow.

- *Debris flows contain a high percentage of coarse fragments and often result from unusually high precipitation. The moving soil and rock debris quickly gains the capacity to move considerable amounts of material at faster and faster speeds. They often follow already existing stream channels and can extend for several kilometres before stopping and dropping their debris load in river valleys or at the base of steep slopes.*
- *Mud flows, on the other hand are made up of fine grained materials (>50% sand-silt-clay-sized particles (Varnes, 1978). They are highly saturated and can propagate and move very quickly. In the international literature there are various classifications of mudflows.*
- *Peat flows are not nearly so well documented in the international literature, they are common in Ireland and the UK, where they are called bog bursts or bog floes. As with other types of materials they have an initial sliding mechanism before becoming a flow. Peat is a very complex material in engineering terms.*

**(2)** SLIDES involve displacements of masses of material along well-defined structures of rupture called slip or shear surfaces. The material moves en masse but it is likely to break up with distance from the initial rupture point.

- *Rotational Slides involve sliding on a shear surface which is concave upwards in the direction of movement where the displaced mass rotates about an axis which is parallel to the slope. The back or crown of the slide is marked by a crack or scarp slope which is concentric in plan. The displaced mass may flow further downslope beyond the rupture surface to form a zone of accumulation at the toe of the total feature, however where the slip surface dips into the hill, the downslope momentum may be arrested somewhat and the sliding stop. Rotational slides can be single events or more commonly multiple events where there are sequential rotational slides down the slope. There is an extensive terminology on the anatomy of landslides (Anon, 1990).*

- *Translational Slides are also called planar slides. The mass of material moves downslope on a largely planar surface. There is little rotary movement and consequently little backward tilting of the earth materials which is characteristic of a rotational slide. Translational slides can have very different impacts to rotational slides. Where the slopes is sufficiently steep and the shearing resistance along the slip surface remains low, the movement can continue on for a considerable distance. This is quite different to rotational slides as described above. This has ramifications for risk assessment and planning controls. Translational slides in rock usually occur along discontinuities such as bedding planes or joints. In the case of debris slides failure can occur on shallow shear surfaces at or near the base of the surface materials where there can be marked changes in strength and permeability. Slopes where discontinuities lie parallel or sub-parallel to the ground surface would be prone to translational sliding.*

**(3)** TOPPLES are a distinct type of movement which can be classified separately to falls. It involves the forward tilting of rock mass along/about a pivot point under the force of gravity. The rock mass may stay in place in this position for a long time or it may fall away downslope due to further weakening or undercutting. This will depend on the rock type, the geometry of the rock mass, and the extent of the discontinuities.

**(4)** SPREADS, In contrast to flows, are characterised by the dominant movement in being lateral extension due to shearing or tensional fractures. In bedrock there may be such extension without controlling basal shear surface (Varnes 1978). Alternatively this extension of coherent rock or soil may be due to plastic flow of a weaker subjacent layer. The coherent mass may subside into the lower layer or it may slide or flow. Spreads can therefore be very complex but are felt to be distinct enough to be classified separately.

**(5)** COMPLEX LANDLSIDES-they involve more than one type of the movement mechanisms mentioned above.

Slope failure can be classified by their position relative to slope geometry into:

1. Slope failure: weak near surface materials and failure through the slope face;
2. Toe failure: extended slope failure through the toe ;
3. Base failure: characterised by a weak zone at depth.

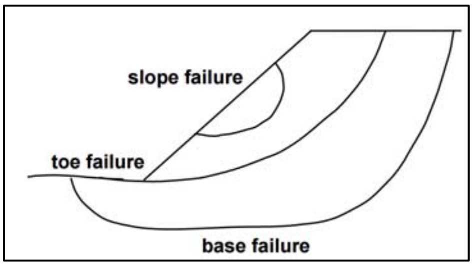



**Figure 3.5 Types of rotational failures within the slope body**

### 3.2.1.1 Influence of change in pore water pressure and stress/strain conditions

**Precipitation and Slope Stability**

According to Yeh et al. (2008) rainfall can induce a rise in the groundwater level and decrease the matric suction (negative pore water pressure) which results in the slope failure. The failure is very often initiated by rainfall and a change in water conditions caused by extreme events such as floods. The measure in the rise of the ground water which contributes to the failure is still unknown, instead, the advancement of the wetting front is introduced as one of the possible intensity measures.

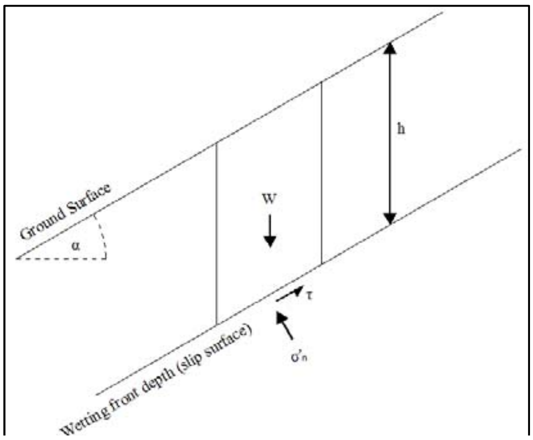



**Figure 3.6 Development of the wetting front in a slope during rainfall**

Wetting front depth is effectively the depth of failure in a planar failure mode. It can be considered that some depths, which are typically less than 0.5 m, are of no consequence to operation and safety of the network. The depth of wetting front which develops 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.

**Progressive Failures in Slopes**
According to Palmer and Rice (1972), in heavily over-consolidated clays there is a marked peak in the observed relation between shear stress and strain. With increasing strain levels, the stress falls from the peak value to a much smaller residual stress state. Failure in such clays is often progressive and it takes place many years after the construction. The slip surface will propagate further into the slope until the pore-water pressures begin to recover (mean effective stresses decrease). Sliding occurs alongside contracted slip surfaces where the mean shear stress is markedly less than the peak shear strength.

**Liquefaction**
This is a phenomenon where a saturated or partially saturated soil loses strength and stiffness in response to the applied stress and starts behaving like a liquid. It is usually caused by earthquake vibrations or other sudden stress conditions, in which the shaking causes a reduction in the pore space of the material and the densification drives the pore pressure in the material upwards. Hazen (1920) first introduced this term, tying it to saturated low density sandy soils.

**Rapid Drawdown**
Rapid changes in hydrostatic pressure acting on the slope surface can lead to changes in total stresses and pore pressure inside the slope, influencing the stress-strain relation in the soil skeleton. This is a common issue with reservoir slopes, embankment dams and anywhere a slope is subjected to rapidly fluctuating water levels.

## 3.2.1.2 Influence of Vegetation on Slope Stability Vegetation

According to Coppin and Richards (1990), vegetation is a cost-effective self-maintaining mechanism for improving slope's stability, and the species used should be selected to meet the specific conditions. Vegetation offers the best long-term protection against surficial erosion on slopes and provides some degree of protection against shallow movement.

Ali et al. (2012) state that by introducing vegetation to the slope, improved hydrological effects involve the removal of soil-water by evapo-transpiration through vegetation, which can lead to an increase in soil suction or reduction in pore water pressure, hence an increase in the shear strength. Apart from increasing the strength of soil by reducing its moisture content, evaporation by plants reduces the weight of the soil mass. Also, the roots act as a mechanical reinforcement to the slope.

The relative effectiveness of vegetation depends on the quality of the vegetation, topography, slope, hydrology and the type of soil. The following figure illustrates the effect of the vegetation on slopes. Grass and small plants provide protection against shallow erosion, whereas the trees, depending on the depth of their roots, provide resistance to deeper potential slip surfaces.

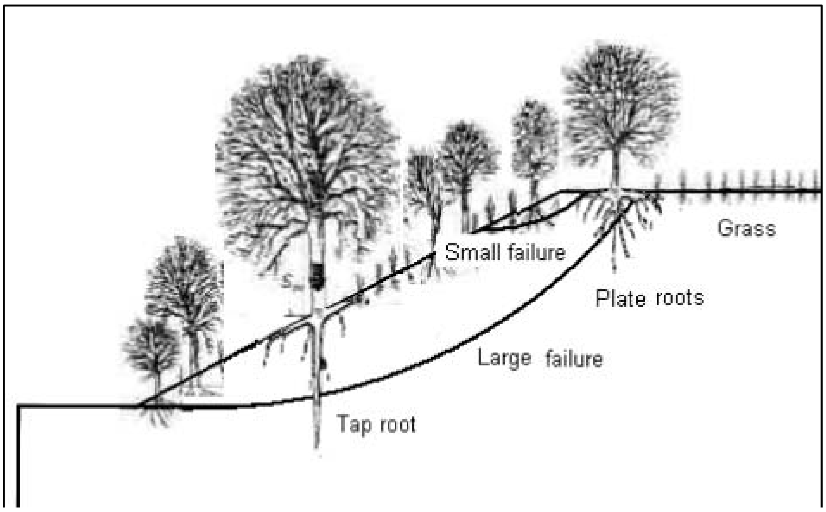



**Figure 1Mechanism of root reinforcement for grass plants and trees**

### 3.2.1.3 Influence of Freeze-Thaw effect on Rock slopes

Freeze Thaw or Frost Weathering is a term used to describe various types of mechanical weathering processes within the rock, where the stresses are created by freezing of water into ice. The process may take from minutes to years, depending on the rock quality and the number of freeze-thaw cycles. This occurrence is mostly pronounced in high altitude areas which are especially associated with alpine, periglacial, sub-polar maritime and polar climates, but occurs wherever freeze-thaw cycles are present.

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$^0$C, but at -22$^0$C, ice growth can generate pressures up to 270MPa, and that is more than enough to fracture any rock.

**Figure 3.8 Rock degradation by freeze – thaw effect**

### *3.2.2 Tools for Risk Analysis of Slopes*

In order to assess the stability of a slope, and to provide a safe design for engineered slope assets, limit equilibrium analysis are necessary. Many geotechnical software applications have implemented well-establish limit-equilibrium methods such as Morgenstern- Price, Bishop, Janbu, Spencer, Ordinary/Fellenius etc. For robust slope analysis, it is essential to implement the appropriate partial factors applied to the soil materials, as specified in the relevant design standards (i.e. EN 1997-Eurocode 7). As an alternative to limit equilibrium methods, Finite Element Analysis (FEA) provides a design methodology which can accommodate complex geometries and localised geological features.

When considering slope assets across a transport network it is important to think of the cuttings, embankments and natural slope topography as a series of geotechnical assets. The objective of slope asset management is to achieve life-cycle performance goals such as safety, mobility, sustainability, environmental aspects in the most cost-beneficial manner. According to Stanley (2011) traditionally, geotechnical asset management along the transportation networks are often neglected because it is vast and considered as laborious and costly. Current road management is primarily based on reactive measures such as restoring the asset to the original condition prior to an event and less on proactive mitigation strategies. By developing a proactive framework and slope asset management plan, human lives, financial expenditure and time can be saved.

Many countries have hazard, risk, inventory or other type of maps concerning avalanches, floods, landslides, rock falls etc. Switzerland is one of the countries that provide a good example, with Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) as the forefront in the data collecting of different natural hazard occurrences in Switzerland. Any kind of data collecting/mapping helps categorise areas in different risk groups which are then combined with other relevant data to provide guidance to road managers/owners on how to proceed in challenging situations.

Another good example is the susceptibility mapping in Ireland which was undertaken by GSI (Geological Survey Ireland) from 2007 to 2013. The susceptibility maps are published at a scale of 1:50 000 and are available in digital data (presented in the figure below). The term susceptibility refers to the spatial distribution of existing and potential landslides. These maps should not be treated as hazard maps, or risk maps.

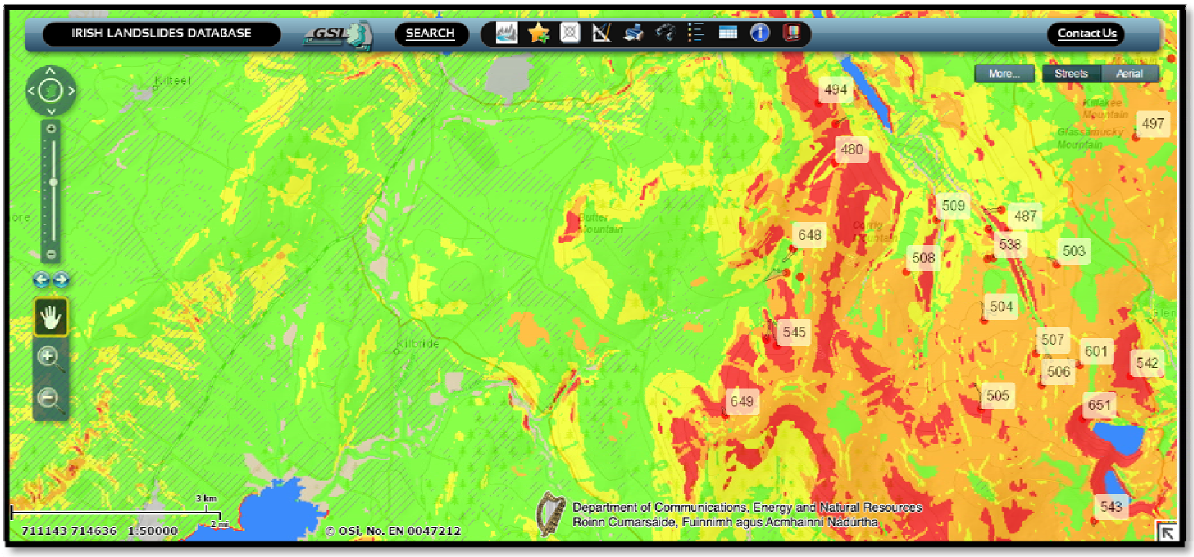



**Figure 3.9 GSI susceptibility map (GSI, 2015)**

The definition of different types of maps according to the GSI are outlined below:

Landslide Inventory Map shows the locations and the outlines of the landslides, may present single or multiple events.

Landslide susceptibility Map ranks slope stability of an area into categories that range from stable to unstable. They also show where landslides may form.

Landslide Hazard Map indicates the annual probability of landslides occurring throughout an area. An ideal landslide hazard map shows not only the chances that a landslide may form at a particular place but also the chances that a landslide from a further upslope may strike that place.

Landslide Risk Map shows the expected annual cost of landslide damage throughout an area. Risk maps combine probability information from a landslide hazard map with an analysis of all possible consequences (property damage, casualties and loss of services).

There are two types of approaches to risk assessment:

1. Qualitative Risk Assessment (likelihood of an event, risk matrices are the most common approach)
2. Quantitative Risk Assessment (quantification of the probability of an event occurring and expression of the losses in real terms which would arise from such an event)

Land Susceptibility Assessments aim to develop appropriate guidance and standards arising from the national inventory of landslide events and mapping of those to show areas where the potential for landslides exist. The final goal is to reduce the risk to human life and the damage to the property. Planning of future infrastructure such as road networks should take into account the findings of these type of maps.

## 3.3 Types of Slopes according to the geographical position

Similar to the approach taken for retaining wall assets, slope assets have been classified according to the geographical environment: Riverside slopes, Seaside slopes, Mountain slopes. It is worth noting that considering Europe as a whole, only a small portion of the infrastructure slopes are located by the riverside/seaside, and mountainous slopes are mostly related to Alpine countries. Most of the engineered cuttings and embankments are well designed and not prone to failures, however there is always a risk for a landslide occurrence which will affect the road slope and the operability of the transport network.

To be more specific, since the focus is on road slopes, they can be classified into up-road slopes and down-road slopes, depending on whether the slope is positioned on the upside of the road or the downside of the road. Up-road being the cutting, and down road being the embankment.

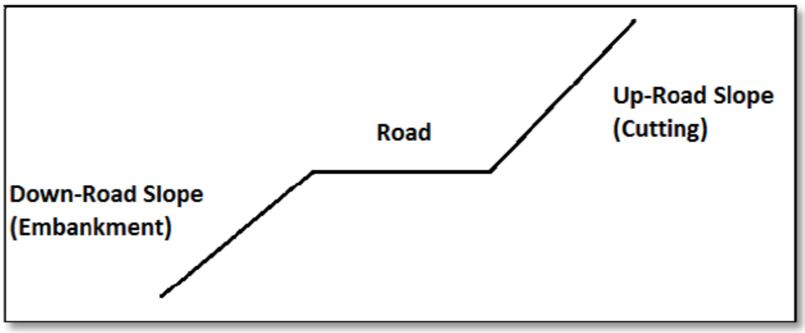



**Figure 3.10 Road slope terminology**

**Mountainous Areas**
There is an increasing tendency observed for storm events and their intensity is also on the rise, especially in autumn, spring and winter. As a consequence the occurrence of shallow landslides in steep mountains will increase. Glacial retreat and the melting of permafrost will cause more landslides, debris flows and rock falls to occur.

**Coastal Areas**
With respect to climate change effects, roads adjacent to the Mediterranean Sea will differs significantly from more northern coastal areas such as those bordering the Baltic Sea. Due to its geographical position, the Mediterranean is highly prone to seismic activity, and landslides and rock falls are often triggered by earthquake events. According to various IPCC reports, the southern regions will become dryer and warmer while the northern European regions will become wetter due to the change in the precipitation and as a consequence that will lead to changes in the salinity and wind regime. Different triggers and degradation mechanism will apply for these two coastal areas. The changes in temperature will also impact on the water table, where fluctuations downward will increase slope stability while rising water tables will decrease slope stability and potentially act as a landslide trigger.

**Riverside**
European has several major river catchments, the biggest observed changes with highest flood events were recently marked in the Danube Catchments with serious flood events in 2013 and 2014. Most landslides are triggered after the flood water retreats and rapid drawdown conditions occur. Furthermore, flood waters adjacent to slopes that are not conditioned for flowing water can cause a scouring effect from the rushing water leading to

toe undermining in the slope and subsequently to its collapse. The following table 3.3 summarises potential landslide scenarios related to climate change effects.

**Table 3.3 Possible landslide scenarios for different geographical locations**

| Natural Surroundings/ Geographical Area | Possible Climate Change Scenario | Local Slope Failure/Landslide Scenario |
|---|---|---|
| Seaside | (a) Increase in sea level<br><br>(b) Higher occurrence of storm surges (wave impacts/ scour)<br><br>(c) Changes in salinity | (a) Seasonal wetting/drying areas are increased, changing the cyclic pore water pressure conditions within the slope body. This will have a significant negative impact on slopes susceptible to progressive failure.<br><br>(b) More frequent and higher and stronger surges directly impact the slope and lead to failure by affecting the slope (toe) which is directly in contact with the waves. This failure mechanism may be linked with scour impacts.<br><br>(c) Changes in the salinity of the water causes changes in the salinity of the soil within the wetting surface which can have negative impacts on the shrink/swell potential of the material and also change the stiffness of the soil mass. (In Norway there are slope failures related to the "Quick Clay". These types of material are particularly sensitive to the salt concentration in the pore fluid within the soil). |
| Riverside | (d) Rapid drawdown after floods<br><br>(e) Increase in water speeds/volumes in the river channels during floods | (d) After the retreat of water following a flood event, the hydraulic conditions within the slope body are changed which triggers large scale landslides due to decreases in the effective strength. Changes in hydrostatic pressure acting on the slope surface, leads to changes in total stresses and pore pressure inside the slope, influencing the stress-strain relation in the soil skeleton.<br><br>(e) Channel stream instability leads to scour of the toe of the slope directly affecting the stability. |
| Mountains | (f) Increased precipitation<br><br>(g) Glacial retreat<br><br>(h) Freeze-thaw cycles | (f) Higher precipitation leads to more frequent occurrence of shallow landslides (debris flows).<br><br>(g) More landslides in general, more rock falls and more debris flows.<br><br>(h) Higher risk of rock falls. |

The following tables (3.4-3.6) show the impact on Up-Road and Down-Road slopes with respect to the geographical location of the infrastructure assets. The same threat has a different level of impact on Up-Road and Down-Road slopes in road infrastructure.

**Table 3.4 1Likelihood of an event for seaside environment**

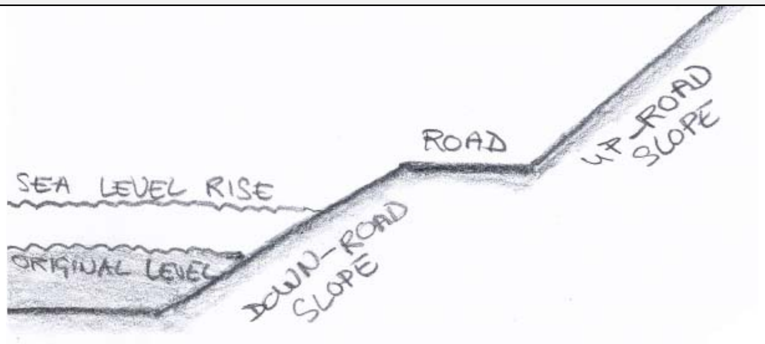
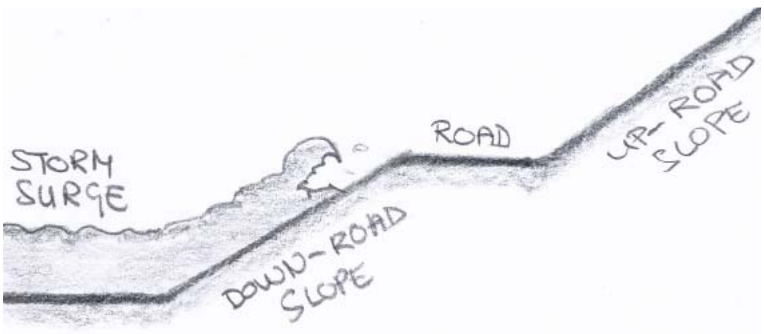
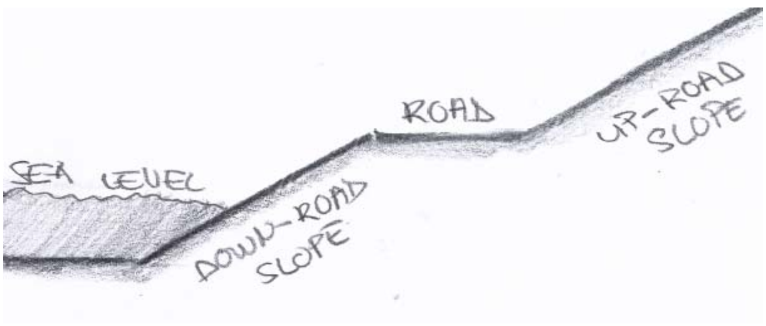
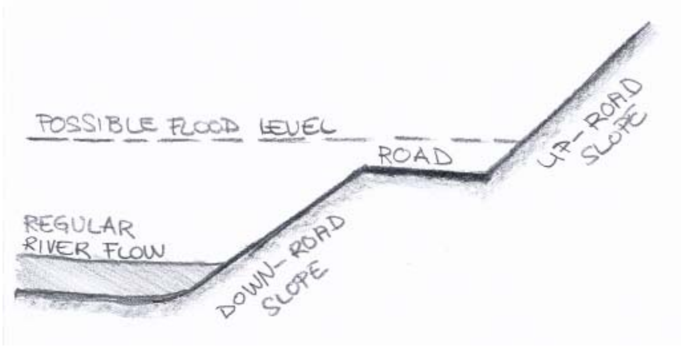
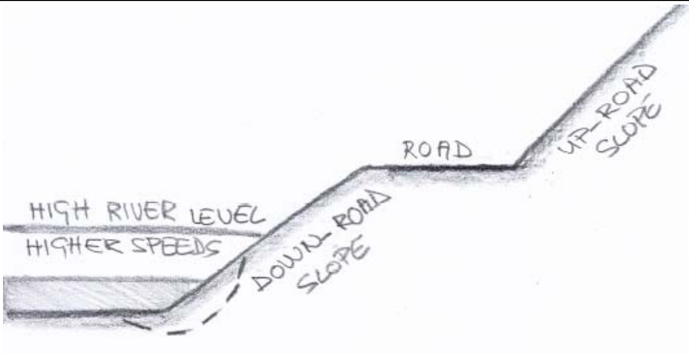
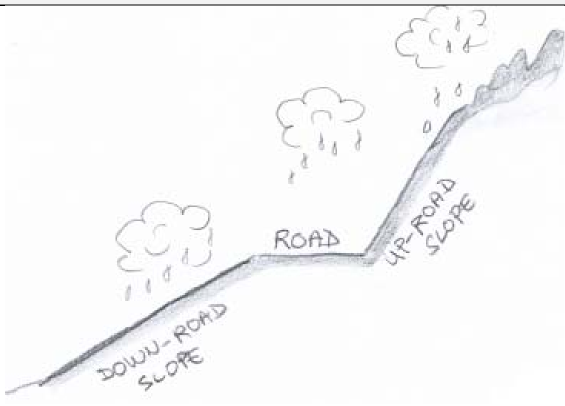
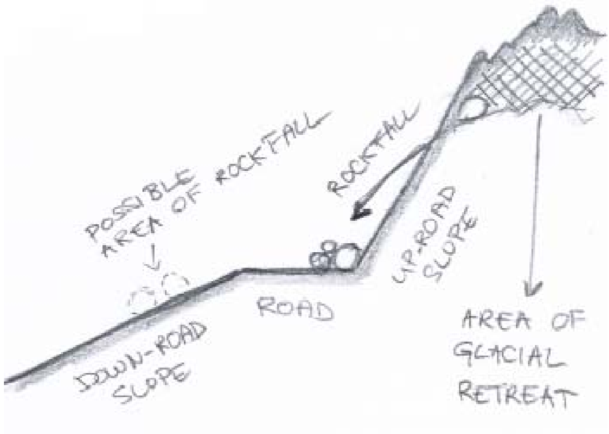
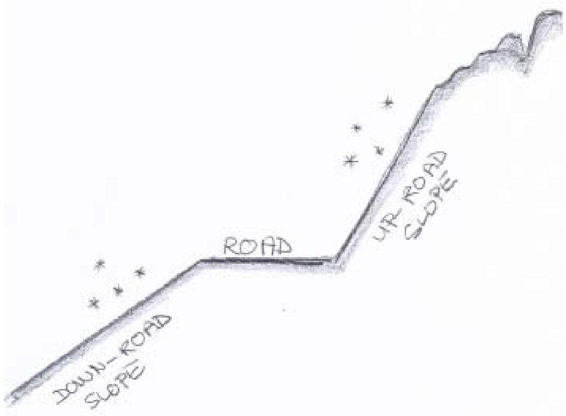
| Seaside Environment | | | |
|---|---|---|---|
| Potential Threat | Illustrative description | Likelihood of an event on Down-Road Slope | Likelihood of an event on Up-Road Slope |
| Increase of the sea level |  | High | Low |
| Higher occurrence of storm surges (wave impacts /scour) |  | High | Medium |
| Change in the salinity |  | High | Low |

**Table 3.5 Likelihood of an event for Riverside Environment**

| Riverside Environment | | | |
|---|---|---|---|
| Potential Threat | Illustrative description | Likelihood of an event on Down-Road Slope | Likelihood of an event on Up-Road Slope |
| Rapid drawdown after floods |   | High | Medium |
| Increase in water speeds in the river channels during floods |   | High | Low |

## Table 3.6 Likelihood of an event for Mountainous Environment

| Mountainous Environment | | | |
|---|---|---|---|
| Potential Threat | Illustrative description | Likelihood of an event on Down-Road Slope | Likelihood of an event on Up-Road Slope |
| Increased precipitation |  | High | High |
| Glacial retreat |  | Medium | High |
| Freeze-Thaw |  | High | High |

## 3.4 Summary

Several landslides and slope failures have occurred in recent years which have negatively impacted on the road network. Local slope failures and larger landslides can be distinguished from each other based on the volume of the mobilised soil; however the failure mechanisms are similar in both instances and are therefore similarly influenced by climate change effects.

Factors which can increase the loads on slope assets include; the increase of the soil unit weight by its wetting (precipitation), the steepening of slopes by excavation or erosion, shock loads (storm surge) and added external loads (from buildings to high snow). On the other hand loss of strength can be caused by changes to the pore pressure regime or by external loads such as vibrations caused by earthquakes, and freezing and thawing action.

Depending on the location of the slope, different triggers apply. Although no statistics are available, it can be noted from observed events in recent years, that mountainous areas are the most critical geographical location, and most likely location for slope failure events. Other critical areas according to recent events in Central Europe include any flood stricken areas that may experience rapid drawdown after floods retreat.

As climate change effects continue to worsen, with further rises in temperature, changes in precipitation, gas emissions and sea level rises, it is almost certain that slope assets will be exposed to further negative impacts which will lead to their deterioration and an increased frequency of slope instability.

# 4 Bridges

## 4.1 Introduction to bridge and identification of critical infrastructure elements

The European road network consists of several types of infrastructure which can be considered to be critical. Bridges are structures that link the road network across obstacles (rivers, canyons, valleys and other) and must be considered to be critical.

Bridges can be divided into different material and design types. Furthermore other parameters such as the bridge span can also be used to classify different bridge types. In this project a rough generalization categorizes the bridges into the following two different categories based on materials:

1. Concrete bridges (Reinforced and pre-stressed concrete)
2. Steel bridges

Each bridge can be subdivided into several sub elements, however some of these sub elements may vary and a thorough list of all elements would be very extensive. A list of sub elements for a bridge would usually include; Superstructure, Abutments, Foundations, Edge beams, Expansion Joints, Safety Barriers, Surfacing/Pavement, Water Proofing Membrane, Bearings, and Drainage System – some bridges could be designed without some of these sub elements, therefore the critical structural elements have been isolated. The critical sub elements are defined as the Superstructure, Abutments and Foundation which are critical for the structural integrity whereas the condition of other sub elements may not be and in the following these sub elements are referred to as secondary sub elements. However, the condition of these secondary sub elements may be critical for the functionality and safety of the bridge.

For the purpose of evaluating the elements and sub elements in relation to deterioration mechanics the following tables 4.1, 4.2 and 4.3 are proposed, concrete bridges, steel bridges and secondary sub elements respectively.

### 4.1.1 Primary deterioration mechanisms for concrete bridges

Several deterioration mechanisms for reinforced and pre-stressed concrete bridges have been identified, please see **Figure 2**. Four of these mechanisms have been identified as the primary deterioration mechanisms relevant to climatic changes. The four deterioration mechanisms are:

Corrosion
Chlorides (External) –33%
Carbonation –17%
Freeze – Thaw –10%
Alkali-Silica Reactions (ASR)– 9%

These four causes of deterioration combined are responsible for 69% of the observed deterioration and therefore focal point of the present paper, data adopted from (Nanukuttan et al., 2012).

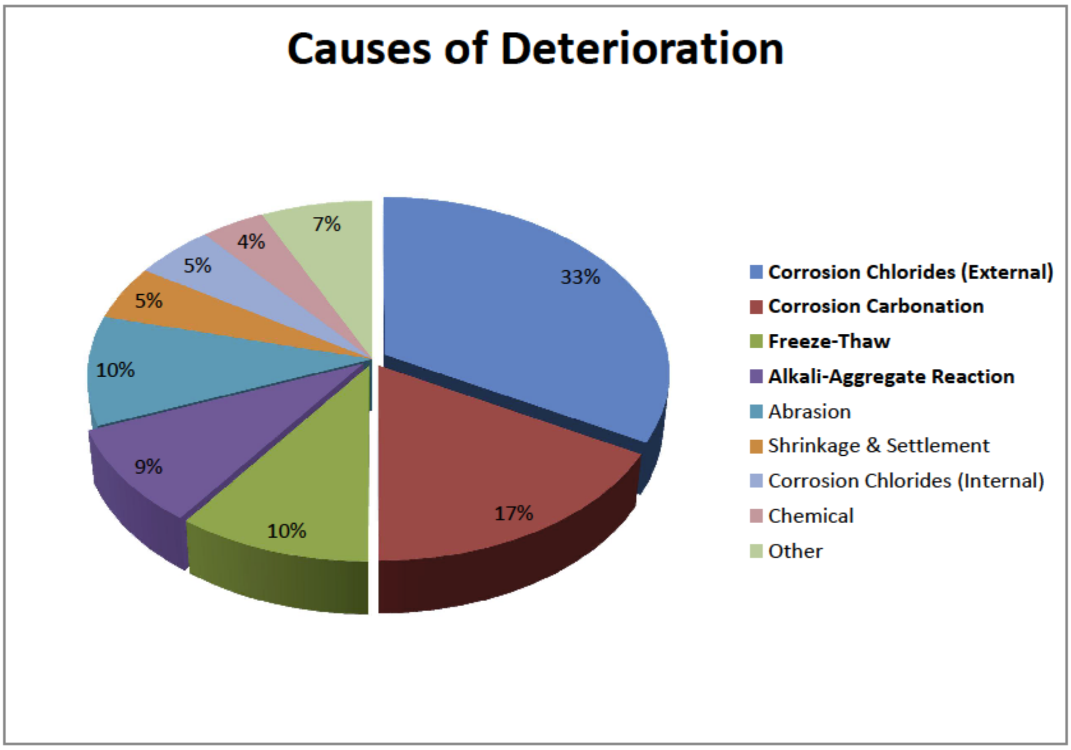
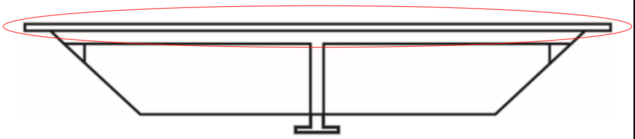
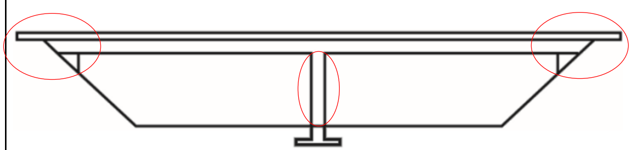
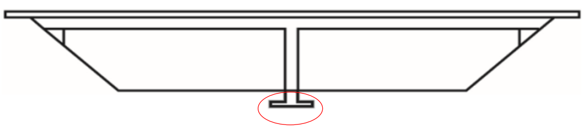



**Figure 2 – Distribution of causes of concrete deterioration mechanisms. Data adopted from**

**Table 4.1 The typical primary elements of a concrete bridge and a risk assessment of the individual elements in relation to climate change.**

| **Sub Element** | **Sketch** | **Deterioration Mechanism** |
|---|---|---|
| **Superstructure** |  | Chloride Corrosion |
| | | Carbonation Corrosion |
| | | Freeze – Thaw |
| | | Alkali-Silica Reactions |
| **Abutments / Supports** |  | Chloride Corrosion |
| | | Carbonation Corrosion |
| | | Freeze – Thaw |
| | | Alkali-Silica Reactions |
| **Foundations** |  | Chloride Corrosion |
| | | Carbonation Corrosion |
| | | Freeze – Thaw |
| | | Alkali-Silica Reactions |

## 4.1.2 Primary deterioration mechanisms for steel bridges

For steel bridges there are two primary deterioration mechanisms, corrosion and fatigue. Corrosion is affected by climate changes whereas fatigue is affected by an increase in traffic, including increased load of traffic and increased traffic intensity. There is a third but not primary deterioration mechanism which is the combination of the two primary deterioration mechanisms which is crucial to the structural integrity of the bridge, corrosion-fatigue.

Corrosion-fatigue is the result of the combined action of an alternating or cycling stresses and a corrosive environment. The fatigue process is thought to cause rupture of the protective passive film, upon which corrosion is accelerated. If the metal is simultaneously exposed to a corrosive environment, the failure can take place at even lower loads and after shorter time. In a corrosive environment the stress level at which it could be assumed a material has infinite life is lowered or removed completely. Contrary to a pure mechanical fatigue, there is no fatigue limit load in corrosion-assisted fatigue, see **Figure** .

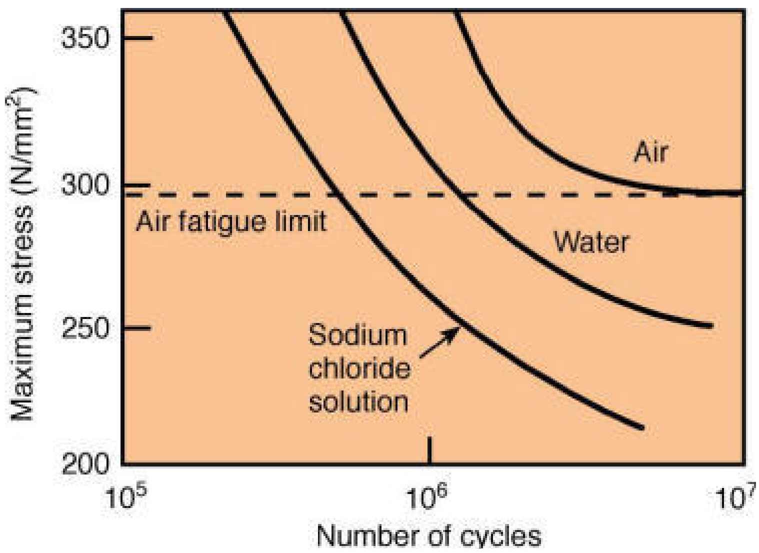
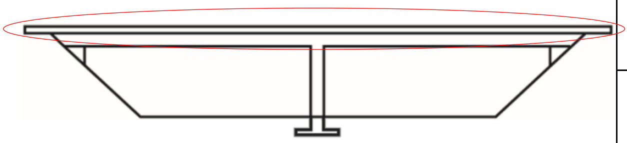
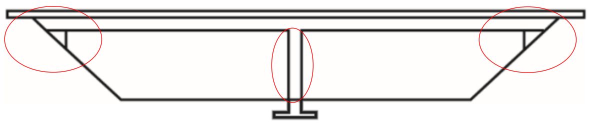
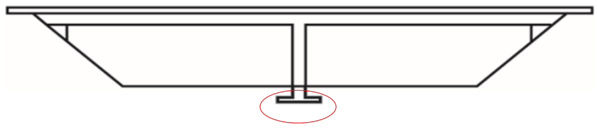



**Figure 4.2 Example of a S-N curve for a structure in air, water and sodium chloride solution (Roberge, 2012)**

Corrosion fatigue and fretting are both in this class. Much lower failure stresses and much shorter failure times can occur in a corrosive environment compared to the situation where the alternating stress is in a non-corrosive environment. The fatigue fracture is brittle and the cracks are most often trans-granular, as in stress-corrosion cracking, but not branched. The corrosive environment can cause a faster crack growth and/or crack growth at a lower tension level than in dry air. Even relatively mild corrosive atmospheres can reduce the fatigue strength of aluminium structures considerably, down to between 75 and 25% of the fatigue strength in dry air (Roberge, 2012).

**Table 4.2 The typical primary elements of a steel bridge and a risk assessment of the individual elements in relation to climate change.**

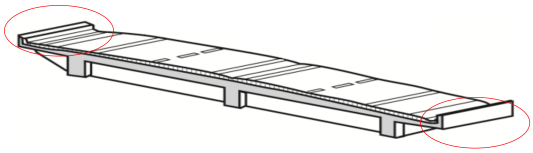
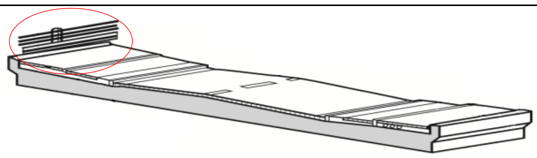
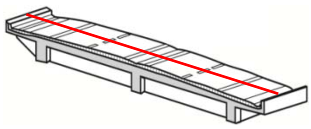
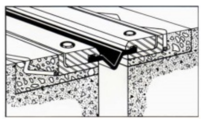
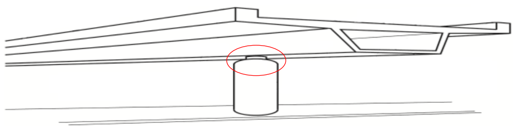
| Sub Element | Sketch | Deterioration Mechanism |
|---|---|---|
| **Superstructure** |  | Corrosion |
| | | Fatigue |
| **Abutments / Supports** |  | Corrosion |
| | | Fatigue |
| **Foundations** |  | Corrosion |
| | | Fatigue |

## *4.1.3 Primary deterioration mechanisms for secondary sub elements*

The secondary sub elements of a bridge can be divided into a wide variety of items and materials and therefore it is difficult to list the primary sub elements of concrete and steel. The category of “secondary sub elements” contains elements that are not fundamental for the structural integrity of the bridge but may be fundamental to the serviceability of the bridge. In **Table** the four most common secondary sub elements are listed in combination with the most common material used for each application.

Surfacing such as asphalt has purposefully not been included in Table 4.3 since surfacing is not only a sub element of a bridge but a sub element throughout the entire transport network. Waterproofing is another element which has been excluded, the reason is that not all bridges have a waterproofing and there can be a huge variation within the selected types of waterproofing, however this is not intended as an inference regarding the importance of waterproofing. If intact, a healthy surfacing (asphalt and/or waterproofing) will lead water (and chlorides from de-icing salt) away from the road and prevent water from reaching the primary elements of a bridge and thereby reducing the risk of deterioration of these elements. Deterioration of the road surfacing can be affected by climatic changes as well as increases in traffic intensity.

**Table 4.3 The typical secondary sub elements of a bridge and a risk assessment of the individual elements in relation to climate change.**

| Sub Element | Sketch | Deterioration Mechanism |
|---|---|---|
| **Edge Beam (Concrete)** |  | Chloride Corrosion |
| | | Carbonation Corrosion |
| | | Freeze – Thaw |
| | | Alkali-Silica Reactions |
| **Safety Barriers (Steel)** |  | Corrosion |
| **Expansion Joints (Steel)** |   | Corrosion |
| | | Abrasion |
| **Bearings (Steel)** |  | Corrosion |
| | | Fatigue |

## *4.2 Location*

It would be impractical to discuss each of the deterioration mechanisms without relating them to their appropriate location. For an example will bridges in the northern EU be more prone to deterioration from freeze –thaw or corrosion from de-icing salts than bridges found in the southern EU, these zones are not only regional but determined by climate, geography and geology and can and therefore vary within the borders of a country or a region. A proposal for these climate zones can be found in (Bunnik, Clercq, Hees, Schellen, & Schueremans, 2010) which is shown in Figure 4.3. The climate zones are described as follows:

- **Bwh** Hot arid climate
- **Csa** Warm climate with hot summers
- **Csb** Warm fully humid climate with dry summers
- **Cfab** Warm fully humid climate with warm to hot summers
- **Dfb** Fully humid snow climate with warm summers
- **Dfc** Fully humid snow climate with cool summers
- **ET** Polar of mountain climate

A change in climate can have pros and cons for the durability and deterioration of a bridge and therefore a combination of a location risk factor and the structural risk factor is advisable to insure that the appropriate focus is given to each of the deterioration mechanisms based on their applicability within the location.

Other local factors, such as risk of flooding and erosion can also be taken into consideration.

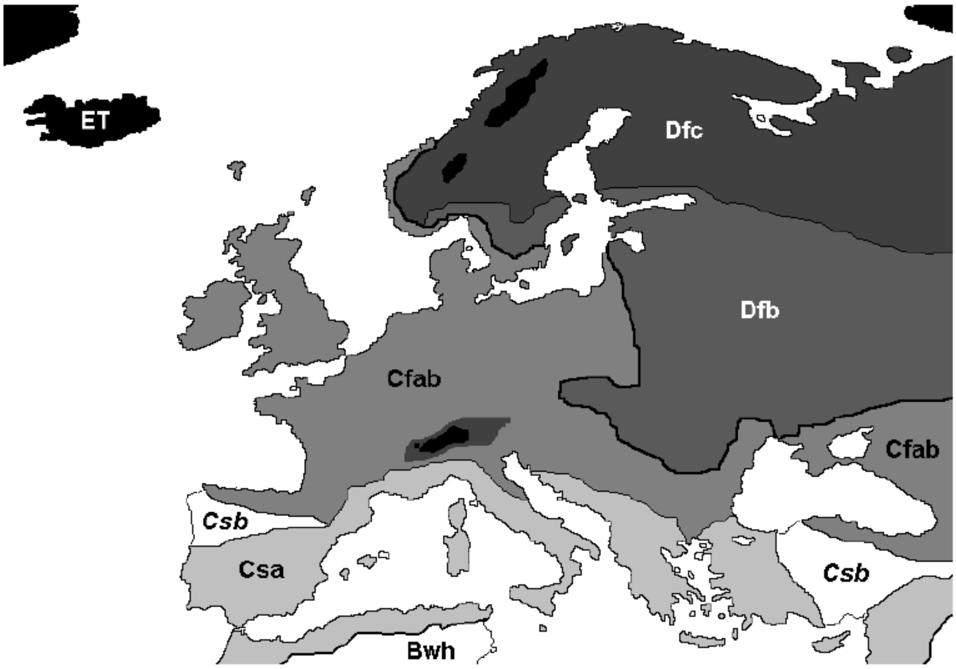



**Figure 4.3 The proposed climate zones for the European continent, adapted from Bunnik et al. (2010)**

## 4.3 Summary

Bridges are categorized into concrete bridges and steel bridges based on materials in this report. Each bridge can contain critical sub elements defined as superstructure, abutments and foundation which are critical for the structural integrity. The main deterioration mechanisms for concrete bridges are corrosion, freeze and alkali-silica reactions; for steel bridges are corrosion and fatigue, where corrosion is mainly influences by climate changes. The deterioration mechanism for sub elements are mainly corrosion, abrasion, fatigue, freeze, and alkali-silica reactions.

# 5 Conclusions

The purpose of this deliverable is to assess the criticality of bridges, steep slopes and retaining walls subject to climate change. In other words, the information collated was used to determine how climate change effects are likely to impact on the future condition of various infrastructure elements.

A detailed review of the published literature was undertaken which identified a dearth of available relevant information. This included limited information on categorizing the importance of road infrastructure with respect to the criticality of various elements exposed to climate change effects (e.g. maximum network disruption, maximum maintenance expenditure, perceived maximum risk to operation, etc.).

The most likely failure mechanisms for different road infrastructure elements were addressed in this report. General information on structural, geotechnical and functional failure modes were considered in order to assess the criticality of bridges, steep slopes and retaining walls subject to climate change. The potential impact of climate change on the future condition of various infrastructure elements were also addressed with respect to the geographical location of the infrastructure. The degradation of infrastructure located in each of the following terrain were considered: (i) Seaside locations; (ii) Adjacent to Rivers; and (iii) Mountainous areas.

General information on structural failures and functional failures of retaining walls were provided. According to the IPCC climate change predictions, it is expected that retaining walls will be exposed to higher carbon concentrations, changes in temperature, humidity and overall air pollution, which will trigger degradation mechanisms such as chloride induced corrosion, carbonation, sulphate attack, alkali-aggregate, alkali-silica and alkali-carbonate reaction. These degradation processes, accelerated by climate change, will reduce the structural lifetime of these assets.

Climate induced changes in rainfall intensity and in particular increasing volumes of precipitation over short durations are of most critical concern for slope infrastructure, where the increasing rainfall patterns will reduce matric suction within the soil body and thereby reduce the effective stress conditions. This in turn will lead to an overall reduction in the slope stability during rainfall events as the slope saturation increases and the margin of safety reduces. The types of slope failures that may impact on road infrastructure could include both local slips and global landslide events depending on the volume of material mobilised. The failure mechanisms for both local slope failures and landslides are similar and both can have dramatic impacts on the road operability, with the remedial solutions often requiring road closures while significant repairs works are undertaken.

The main deterioration mechanisms for concrete bridges are seen to be corrosion, freeze and alkali-silica reactions; whereas for steel bridges corrosion and fatigue are the dominant mechanisms. In terms of climate change effects, corrosion is the primary degradation mechanism affected. This report summarises the various failure modes for bridge structures subjected to changing climatic conditions.

# 6 Acknowledgement

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# Annex A-Summary of Literature Review

## A.1 CEDR project RIMAROCC

The objective of the RIMAROCC project, standing for Risk Management for Roads in a Changing Climate, was to develop a common ERA-NET ROAD method for risk analysis and risk management with regard to climate change for Europe. The details of the project were covered in the 2010 final report. More specifically, this method enables the user to identify the climatic risks and to implement optimal action plans that maximise the economic return to the road owner taking into account construction cost, maintenance and environment.

A risk framework is developed (See Figure A.1) to adapt to climate change. The RIMAROCC framework consists of seven steps, each with a number of sub-steps.

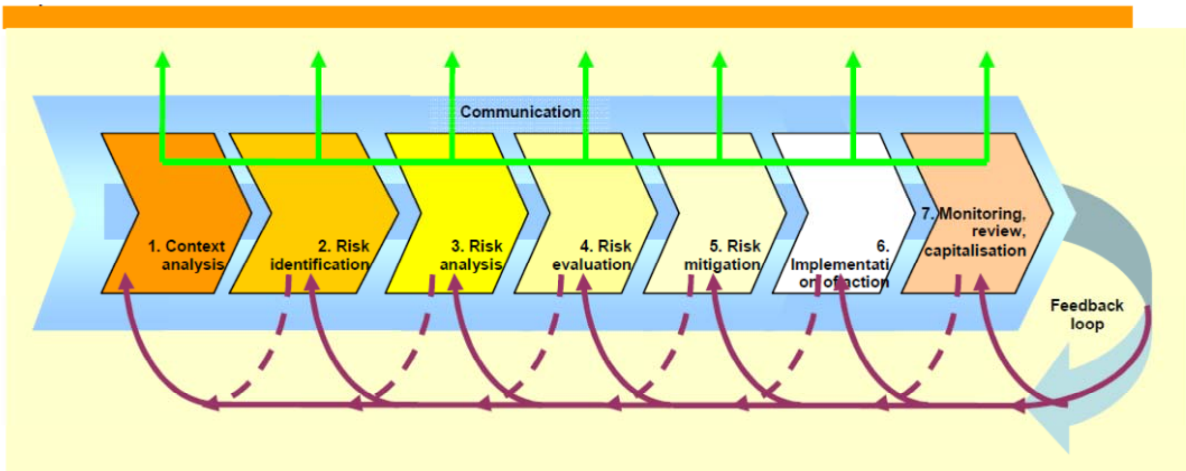


**Figure A.1 RIMAROCC risk framework with feedback loop (RIMAROCC, 2010)**

Step 1 determines the possible consequences of climate risks and their related indicators. Step 2 identifies risk sources and vulnerabilities and possible consequence. The objective of step 3 is to establish risk scenarios, determine the impact of risk, evaluate occurrences and provide a risk overview. Step 4 is risk evaluation with quantitative aspects and step 5 is risk mitigation with appraise options, followed by step 6 implementation of action and feedback loop.

In RIMAROCC, the choice of the scale of analysis is a top-down approach, from an overview on a network scale to a detailed analysis of a specific structure.

- Territorial scale: identify territories serviced by the road network. This is the stage on which the climate event could affect most or all of the territory. It is the only scale of analysis where all the territorial stakes related to the road network can be addressed. Authorities responsible for various sectors co-operate to adapt the territory to climate change. For the territorial scale, the National Road Authority could be one such authority.
- Network scale: identify the main vulnerabilities in a road network before focusing on critical sections, nodes or structures. Both territory and network scales correspond to strategic approaches, based on climate scenarios and qualitative analysis (expertise) of vulnerability and consequences.

- Section scale: analysis in the section scale is either conducted prior to the network scale consolidated approach when critical sections are already known (high levels of traffic, no alternative route, sensitive environment …), or after having identified the vulnerable sections through the network approach in order to refine the analysis
- Structure scale: orientation is devoted to analysing critical points of a section, such as a viaduct, a tunnel, a node (interchange), etc. These critical points can be identified through the network and/or section approach. As the analysis focuses on a single object, it is easier to implement a comprehensive and technical (quantitative) approach.

The focus of RIMAROCC was to build a conceptual framework for road authorities to identify the critical part of roads which are sensitive to climate change. However, it is worth noting that the report did not identify the asset classes of road infrastructure that cause maximum concern nor the critical elements of road infrastructure. After contacting the authors of this report, they also confirmed that the information on categorization of critical road infrastructure is not available.

However, RIMAROCC report mentions that if the analyst …"*can break the system down into components, one can get a grip on the risks…:*

- *pavements*
- *bridges*
- *equipment (e.g. road signs, lighting, safety barriers)*
- *small hydraulics (drums) and drainage*
- *geotechnics*
- *environment*
- *large hydraulics (culverts)*
- *sea level"*

In addition, in the network scale study the RIMAROCC project defines vulnerability as the extent to which a natural or social system is susceptible to sustaining damage from climate change. It is a function of the sensitivity of a system to changes in climate, adaptive capacity and the degree of exposure of the system to climatic hazards. Studies of vulnerabilities in RIMAROCC include:

a. Sensitivity and exposure of an asset (road, right-of-way, equipment, maintenance vehicles, etc.) to risk factors and/or to unwanted event
b. Traffic
c. Age
d. Design standards
e. Maintenance practice (routine and heavy repairs)
f. Adaptability of an asset, i.e. possibility of upgrading without a complete reconstruction of the asset.

RIMAROCC suggests that these studies can be carried out through surveys by the technical and operational staff of the Road Authorities.

For each element of the road system, information will be collected on the vulnerability of the sub-elements (embankment, pavement, hydraulics, etc.) for each possible risk identified. Each sub-element/vulnerability should be defined in a "National Vulnerability Reference Manual" or equivalent (a database, for example). If such a frame of reference does not exist, the analysis of the road system vulnerability should start at an early stage in the risk management process review, in step 1 of Figure 1. This survey can be carried out through surveys by the technical and operational staff of the Road Authorities.

Data to be collected include the following:

- Infrastructure-intrinsic factors: construction date, standards used, materials,
- Equipment, etc. with a level of precision depending of the scale of analysis.
- Data covering actual traffic and a comparison with expected traffic: number of vehicles, type, origin destination analysis, etc.
- Data regarding maintenance (routine and heavy repairs).
- Structural defects or existing damages likely to be worsened by climate factors.
- Etc.

The main infrastructure components to be investigated are: major hydraulic structures (e.g. Dams), minor hydraulics and drainage, engineering structures, equipment, geotechnics, environment and pavement.

## A.2 CEDR project ROADAPT

The CEDR project ROADAPT was the acronym for “Roads for today adapted for tomorrow”. The handbook of ROADAPT was not available to the public when this report was written. Therefore the review of this project was completed by attending the workshop held in October 2014 and throughout the handouts from this workshop.

The ROADAPT project was a response to the CEDR call objective of prioritizing adaptation measures in order to maximize availability within reasonable costs. It adopts a risk based approach using the RIMAROCC framework that was developed within ERA NET ROAD in 2011. The approach addresses cause, effect and consequence of weather related events to identify the top risks that require action with mitigating measures. Specifically, the programme is based on the three objectives:

A. Identification and modelling of climate change effects regarding national highway networks to provide a unified input data base;
B. Development and application of risk based vulnerability-assessment of transnational highway networks (TEN-T);
C. Development and application of adaptation technologies.

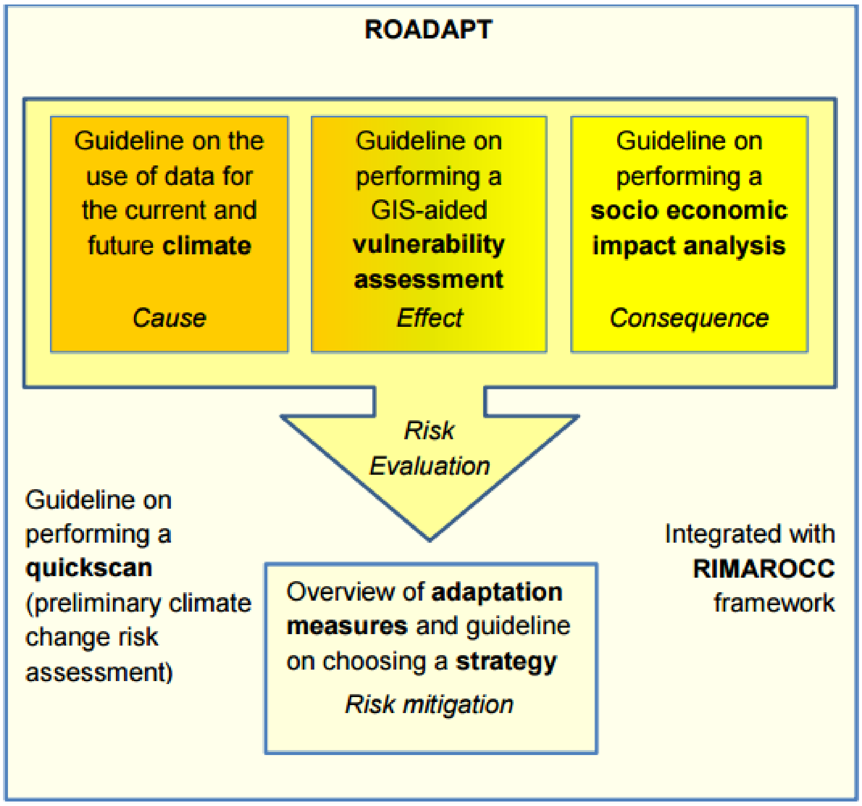


**Figure A.2 Brief structure of ROADAPT research (Deltares, 2014)**

The details of this research are similar with the research process of RIMAROCC.

In this report, the bridge and culvert are identified as particularly vulnerable. The different threats that lead to infrastructure failures are extracted in the following table:

**Table A. 1 The Threats form climate change impact on infrastructures**

| MAIN THREAT | SUB THREAT | VULNERABILITY FACTORS | IMPACT (recover time) |
|---|---|---|---|
| Flooding of road surface (assuming no traffic is possible) | pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads) | Earthworks, bridges, culverts, drainage | days - weeks |
| | Flooding from snow melt (overland flow after snow melt) | Culverts, ditches | days - weeks |
| Erosion of road embankments and foundations | Overloading of hydraulic systems crossing the road | Culverts | week - months |
| | Bridge scour | Bridges | months |
| Loss of road structure integrity | Impact on soil moisture levels (increase of water table), affecting the structural integrity of roads, bridges and tunnels | Pavements, bridges and tunnels | days - weeks |
| Landslips and avalanches | External slides, ground subsidence or collapse, affecting the road (including eg. embankments aside the road) | Natural slopes, underground cavities, loss of vegetation | days - months |
| | Slides of the road embankment | fill slopes, retaining walls, embankment materials, slope angle (higher slope angle = higher vulnerability) | weeks - months |

In conclusion, this report is the subsequent report of RIMAROCC where the scenarios of climate change have been taken into account. The vulnerability of infrastructures are identified (the same as RIMAROCC: pavements, bridges, equipment, small hydraulics, geotechnics, environment, large hydraulics, sea level”). However, the components of each infrastructure are still not further analysed.

## *A.3 A Review of the resilience of the transport network to extreme weather events*

This report (GB Department of Transport, 2014) undertaken by the U.K. department of transport was issued after the winter of 2013/14 when the UK experienced some of the most extreme weather. This document tries to answer two main questions:

(1) How the transport systems could be made more resilient, so as to reduce the level of disruption from extreme weather in future.

(2) Produce practical recommendations on how they can strengthen the resilience of their transport systems and learn the lessons from 2013/2014 winter.

For this purpose, this report not only covers the road network (strategic road network and local roads), but also railways, ports and airports. They review these assets in different extreme weather, such as: intense rainfall, strong wind, heat waves, storm and other weather hazards.

In the main body, firstly, the authors review primary weather risk impact on transport system and illustrate some case or data in history record. Secondly the event of autumn and winter 2013/14 in UK is analysed as the case study and recommendations are carried out for transport authority, such as: Department for Transport (DfT). Thirdly, some common issues across transport modes facing the extreme weather, are pointed out; later on, the specific issues for different transport modes are addressed separately. With a specific case such as the 2013/14 UK disaster, the authors give their recommendations to improve the transport system's resilience.

> *For instance, in the winter 2013/14 UK, the South West peninsula was perceived to be at threat of being 'cut off' through a combination of coastal storm damage to the Great Western main line on the railway at Dawlish. Flooding at Cowley Bridge between Taunton and Exeter on that same line, fluvial flooding of the Somerset Levels severely affecting rail capacity and groundwater flooding affecting strategic road sites such as the A303 and A36.*
>
> *From this case, they give a conclusion that the potential 'single points of failure' in the strategic transport networks, which leave parts of the country at risk of having vital economic and social links severed. Therefore, the commendation for DfT is that they should work with researchers to identify the potential 'single point' and deal with the possible failure.*

In the Strategic Road Network (SRN) part, similar with the example above, the authors analyse the 2013/14 UK event and give recommendations. They also identify three extreme weather events which will contribute to the SRN disruption, such as: snow and ice, high wind and flooding. In this part, they also highlight the two extreme weather events examples (high wind and flooding) and their impact on network: (i) Wind event (a tree blocking the A36 in Hampshire) and (ii) flooding event (flooding on the A303 near Ilchester, Somerset), which both resulted in road cut off. General recommendations about managing road and user behaviour, while ensuring priority for resilience, are carried out at the end.

In the scope of local roads, they mention the structure of local road assets e.g. bridge, embankments, cuttings, retaining walls and culverts. However, the authors did not analyse the specific components of any infrastructure.

The importance of different infrastructure are mentioned in the report:

Culvert:

- “Clearing out of drains, ditches and culverts, this activity is vital to prevent subsequent, more expensive repair work, and in the case of drainage, to allow the asset to work as designed.”
- “The drainage of all roads on the network is also a key issue for highway authorities.”
- “if drains are not cleaned out, their capacity is much reduced and excess water will stay on the road surface for longer. Similarly, if drainage ditches alongside highways, or culverts are not kept clear, or pumps are not kept in good working order, water will not drain away as intended and the result is flooding on the highway. Maintenance is therefore a vital activity to prevent, or at least minimize the impact of flooding resulting from heavy rainfall.”
- “Clearly, drainage systems are a key part of the road network.”

Bridge:

- “Bridges are a particular concern, not least because they can be very important to maintaining resilience.”
- “A particular concern in respect of bridges is ‘scour’. Scour is compounded by the abrasive effect directly on bridge structures themselves by debris (e.g. tree trunks) thrown at structures by rivers in flood, and by such debris becoming lodged against the bridge. These factors were found to be present in the collapse of 3 road bridges and 3 footbridges in the Cumbrian floods of autumn 2009.”

Others:

- “Damaged road surfaces, and particularly potholes, can also cause damage to vehicles.”

In conclusion, this document is based on what was learnt from the experience of 2013/2014 winter events with an aim to improve the resilience in the UK. It gives practical recommendations to help different authorities strengthen the resilience of transport systems. The transport system in this review means: strategic road network, local roads, railways, ports and airports. They focus on snow and ice, high wind and flooding.

For the local roads, they believe asset management, drainage engineering and bridge maintenance are important. Although they analysed the importance of the bridge and drainage system in local roads level, they do not mention the criticality of specific components of these infrastructure.

## *A.4 Common Criteria for the Assessment of Critical Infrastructures*

A paper authored by Fekete (2011) describes the project funded by KritisKAT at the Federal Office of Civil Protection and Disaster Assistance in Germany. The goal of this project is to develop generic criteria for the identification and evaluation of infrastructures regarded as "critical" for society. The paper starts with a conceptual discussion of the terms "critical" and "criticality". The main outcome of this paper is to develop common criteria generally applicable to a variety of infrastructures, e.g. traffic, logistics chains, etc.

The author establishes critical criteria for infrastructures (not limited to roads), and suggests three common criteria as shown in Table A.2.

**Table A. 2 Common properties of criticality criteria**

| Generic criterion | Definition |
|---|---|
| Critical Proportion | Critical proportion summarizes many aspects commonly denoted as most important in the assessment literature. Contains aspects such as the critical number of elements or nodes of an infrastructure, choke points, as well as critical number of services, size of population, or magnitude of customers affected. |
| Critical Time | Critical time summarizes aspects such as duration of outage, speed of onset, specific critical time frames. |
| Critical Quality | Critical quality summarizes aspects such as the quality of the service delivered (for example water quality), and includes public trust in quality. |

The author provides broad and general definitions for criteria so that the criteria can be applied for different types of risk analysis and for different types of infrastructure. The author suggests that the broad common criteria of criticality must be adapted and made more explicit for the infrastructure that is being studied. Table A.3 shows criteria that can be derived from the three generic criteria shown in Table A.2.

**Table A. 3 Nonexhaustive criteria for various infrastructure types (Fekete, 2011)**

| Generic criterion | Examples of specific criteria | Examples of applications (many criteria are valid for almost all types of infrastructure) |
|---|---|---|
| Critical proportion | Load, capacity, power, sales, turnover, etc. | Traffic, logistics chains, power installed |
| | Number of assets, nodes, interdependencies, redundancies, emergency capacities | Backup systems for power or information storage; emergency power |
| | Amount of customers supplied | For instance, the number of people supplied with drinking water |
| | Outreach / spatial interconnectedness | The single chemical plant in the world producing a key product |
| Critical time | Failure duration | Air traffic grounding due to volcanic ash |
| | Mean time to repair, replace, restore the functionality | Replacement time for a transformer station |
| | Mean time to react | Police, fire brigade, medical units, media, early warning, crisis management |
| | Timing of failure | Coldest winter day; annual meeting of company leaders; day of distribution of welfare or pay checks |
| Critical quality | Product or service quality | Water or food quality, trust in finance, training of staff, feeling of security |
| | Cultural or societal significance | National cultural icons |

In general, this paper focuses on giving guidelines on common criteria for critical infrastructures. To meet the goal of Deliverable 2.2, the proposed criteria is useful in identifying the criticality in infrastructure level but less practical in infrastructure elements level.

## A.5 Road Infrastructure cost and revenue in Europe

This report (CE Delft, 2008) is produced within the project “Internalisation Measures and Policies for all external cost of Transport (IMPACT)” commissioned by European Commission. The central aim of the IMPACT study is to provide an overview of approaches for estimating and internalising the external costs of transport. The report contains three deliverables:

1. Deliverable 1 - Handbook on external cost estimates;
2. Deliverable 2 - Report on road infrastructure costs, taxes and charges;
3. Deliverable 3 - Report on internalisation strategies.

These deliverables cover environmental, accidents and congestion costs.

In this report, the road networks of the 29 EU countries are classified into three basic types of infrastructure: (i) motorways, (ii) other trunk roads and (iii) local and urban roads. More specifically, in the cost categorization, the components of road have been listed as following: substructures (base and frost protection course), superstructures (binder and surface courses), bridges, equipment (traffic signs, etc.) and park and rest facilities. Bridge structures are singled out as an asset only in order to calculate cost, and this also means that neither bridge nor its components are analysed any further.

## *A.6 ERF-European Road Statistics*

ERF annual publication (2011 and 2012) contains statistical data on the road transport sector in the following area:

- General data
- Road network
- Infrastructure financing
- Road maintenance and investment
- Goods transport
- Passenger transport
- Safety
- Taxation
- Environment

The information presented in the reports are all at the aggregate level, but not in asset level or infrastructure level. For instance, figure A3 and A4 show the investment in inland transport infrastructure and road maintenance expenditure from 1995 to 2009. Therefore, this information is not useful for the aim of deliverable 2.2.

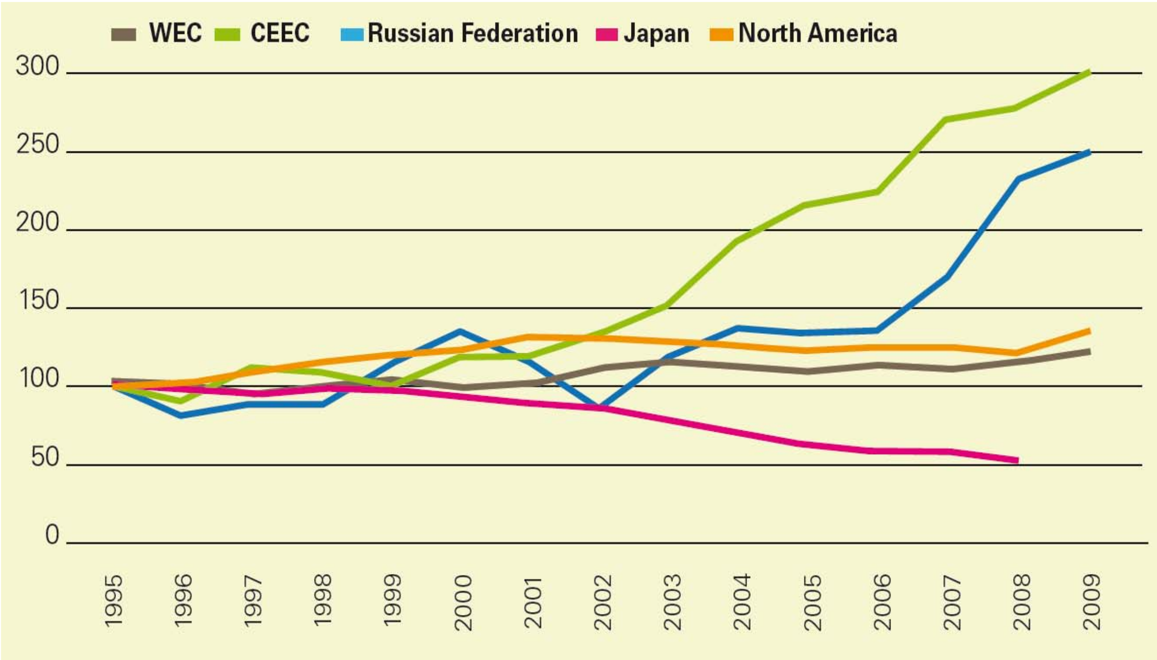


**Figure A.3 Investment in inland transport infrastructure 1995-2009**

**WECs** include Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Spain, Sweden and the United Kingdom. **CEECs** include Albania, Croatia, Czech Republic, Estonia, FYROM, Hungary, Latvia, Lithuania, Montenegro, Poland, Romania, Serbia, Slovakia and Slovenia. **North America**: United States data 2003-2009 estimated. Public road investment based on Bureau of Economic Analysis data on Investment in Government Fixed Assets (highways and streets). **Japan**: not including private investments.

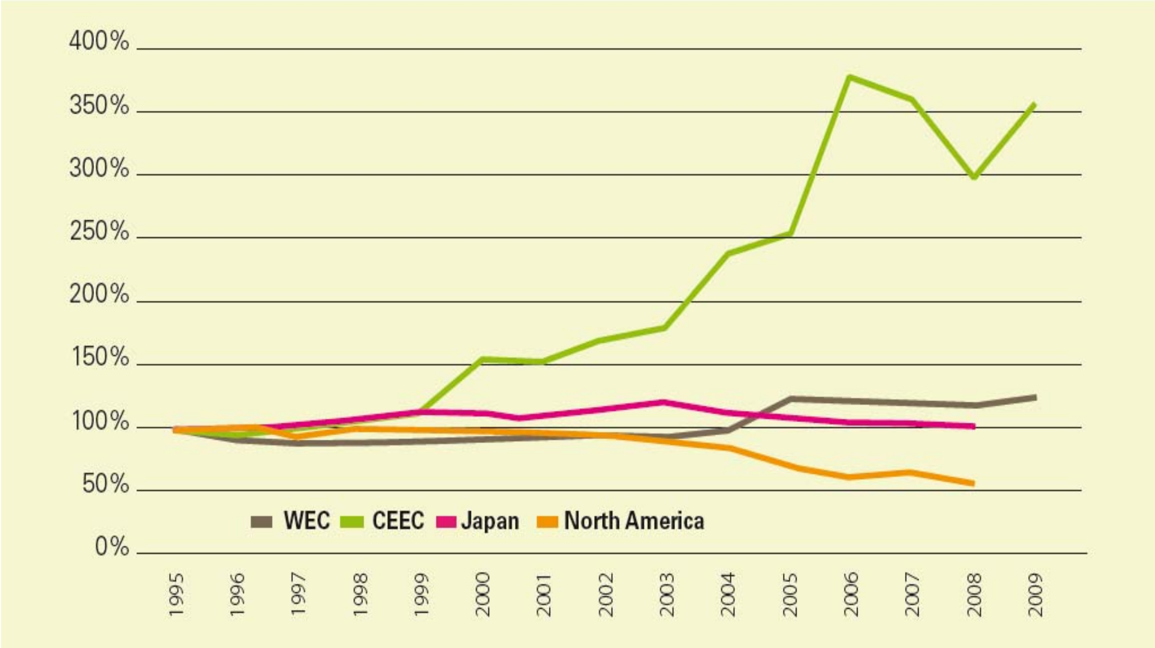


**Figure A.4 Road maintenance expenditure 1995-2009**

## *A.7 CEDR Trans-European road network*

The TENT-T 2011 report was the second biennial VEDR report on the performance of the trans-European road network, TEN-T roads. It showed the state of the art of the TEN-T road networks on 1 January 2011. The 2009 report covered 17 countries and 61% of the TEN-T road network and a limited number of performance indicators. The 2011 report included data from 20 countries and covers nearly 78,000 km or 83% of the TEN-T road network. This network represents the most important roads in Europe.

The number of performance indicators had also increased in the 2011 report. They define the twelve performance indicators categorized into two group: structure of the network and performance of the network (shown in figure A.5). The report shows the comparisons among the EU countries in different indicators.

| Structure of the network | Performance of the network |
|---|---|
| Road Type | Average Traffic Flow |
| Number of Lanes | Traffic Density |
| Length of Bridges | Proportion of Heavy Goods Vehicles |
| Length of Tunnels | Heavy Goods Vehicles Traffic Flow |
| Road Environment | Fatal Accident Rate |
| ITS and PPP Schemes | Performance of ITS Sections |

**Figure A.5 The indicators for performance comparison**

ITS item in this form means: Whether or not the relevant section includes an Intelligent Transport System (ITS). PPP Scheme means: Whether or not the relevant section includes one or more Public–Private Partnership (PPP) Scheme.

In conclusion, these reports (TEN-T 2011 and 2009) show that it is possible to produce comparable information on the performance of the TEN-T road network within the majority of CEDR member states. This report has highlighted the differences between the centrally located countries in Europe and remote European countries, based on a wide range of characteristics present across the European network.

Additionally, we can find that the road assets are divided into different infrastructures, such as: lands, bridges, tunnels, environment (urban, rural, or mountain) and road types (motorway, expressway, ordinary). However, the specific components of these infrastructure have not been mentioned in this report.