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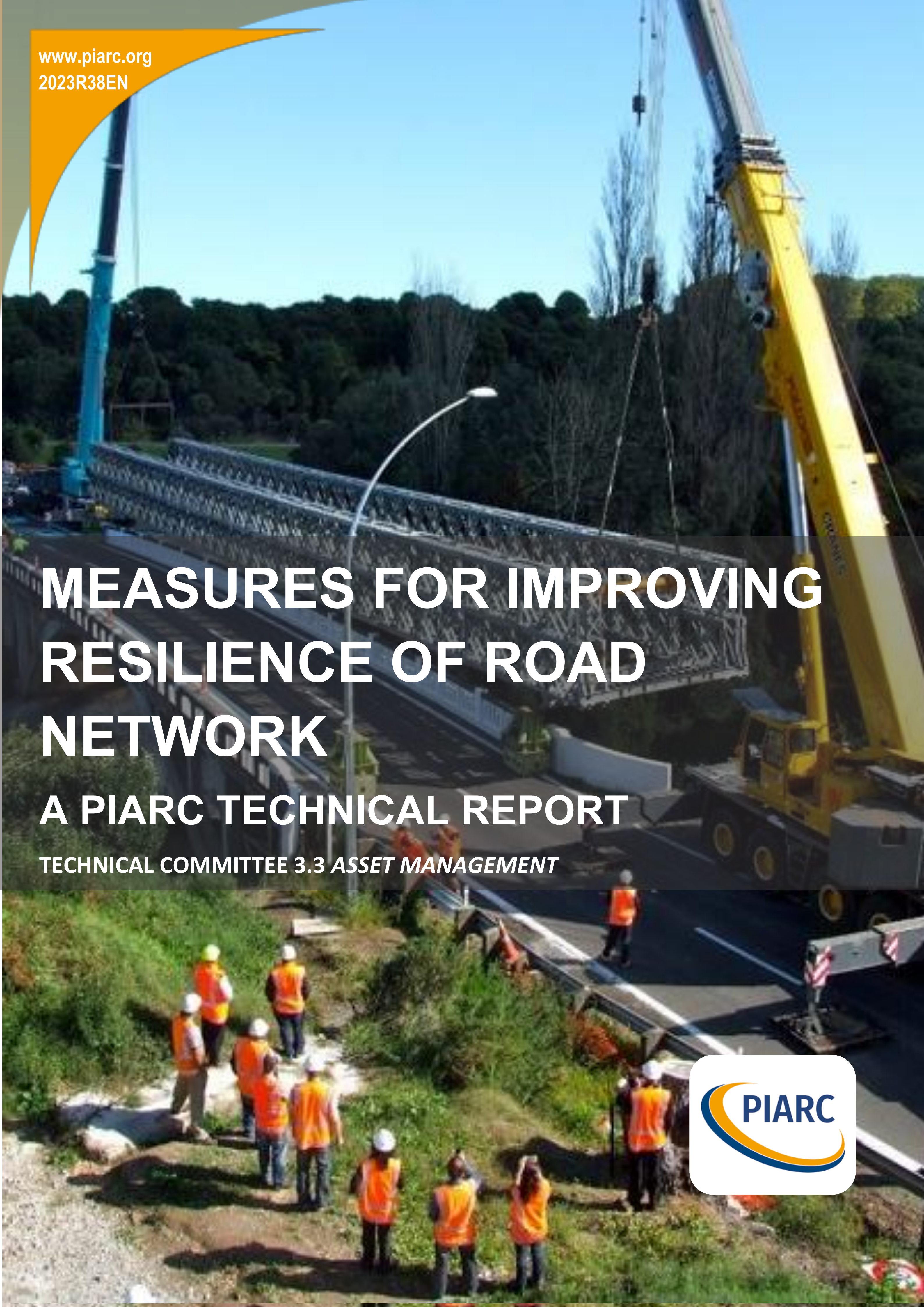

MEASURES FOR IMPROVING RESILIENCE OF ROAD NETWORK

A PIARC TECHNICAL REPORT

TECHNICAL COMMITTEE 3.3 *ASSET MANAGEMENT*

PIARC

STATEMENTS

The World Road Association (PIARC) is a non-profit organization established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020– 2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and don't necessarily reflect the views of their parent organizations or agencies.

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Front cover: Recovery of the Narrows Bridge on SH 21, New Zealand, 2022; ©NZTA

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EXECUTIVE SUMMARY

2023R37EN

MEASURES FOR IMPROVING RESILIENCE OF ROAD NETWORK

A PIARC TECHNICAL REPORT

Transportation infrastructure is vulnerable to threats such are natural and man-made hazards and each agency needs to improve their own ability to adequately and decisively respond to sudden and unforeseen challenges to infrastructure performance. It is pivotal for countries to learn from past experiences to form a shared view on possible future development of transportation networks and how to improve current management approaches to be flexible and adaptive to address future threats, which are likely to be more damaging due to climate change. However, the complexity of approaches being developed depends on the experience of the road operator with natural hazards. Usually, the trigger for improvement of current procedures is related either to a recent hazard event that had a severe impact on network users and society or to a frequently occurring event of a lesser magnitude and consequences thereof.

The report shows that road owners/operators currently apply measures that are aimed at evaluation of asset performance, infrastructure protection, preservation and recovery after failures, which is along the lines of a resilience-based framework. However, there is a need to embrace resilience as a core component of decision making. This will provide valuable insights on potential vulnerabilities in network and the capacity of infrastructure to withstand and recover from disruptions. This important information supports road agencies in prioritisation of maintenance projects fostering the long-term sustainability and adaptability of their infrastructure assets in the face of threats.

The terminology used in the report and the background on evaluation of resilience aspects: robustness, redundancy, rapidity of response and resourcefulness is discussed in the beginning, while the main body of the report is a collection of examples from practice on measures to improve resilience aspects. The approaches in practice comprise planning of preventative maintenance measures, which target reduction of threat magnitudes, mitigation of failure probability/rates of assets and further, mitigation of consequences of failure and recovery measures. The agency-wide approaches that incorporate resilience aspects in a decision-making process are discussed at the end of the report. The variety of presented examples allows that a broad audience of owners/operators of road infrastructure coming from low to high-income countries can relate to similar issues and learn from the experience of others.

CONTENTS

1. INTRODUCTION

1.1 MOTIVATION

Roads have been designed and built for the transportation of people, goods and services for many thousands of years (Figure 1.1). While the vehicles using these roads have changed substantially, the basics of road building have remained much the same. Some of the ancient roadways that were built a few thousands of years ago using natural building materials had generally 1.0 to 1.5 m in thickness, can still facilitate transportation today (Figure 1.1b).

a) b)

Figure 1.1 Examples of ancient roadways. a) Kunigami-Toward West Sea Road, Okinawa, Japan; b) Appia Antica, Rome, Italy; @Hein, D.

With the move to industrialization and globalization, there has been a dramatic shift of human habitation from agrarian to urban communities. This had resulted in the need to significantly expand the availability of goods and services and to do so has resulted in the rapid expansion of the global road network.

The improvement of roads has been one of the major issues that road agencies around the world have had to address in the past 30 years. This is not only related to the workload within agencies but it is also due to ever-changing budgetary allowances and restrictions. The demand for additional and improved roads is not only pertinent to large and dense population centres but has also become important for roads with less to moderate traffic, where there are circumstances that have not been addressed within the practice of road asset management until now. The road asset management practice is predominantly focused on maintenance, which encompasses intervention(s) that remedy damage due to deterioration and traffic. In these cases, the functional properties of the asset remain unchanged, e.g., number of lanes, posting, noise emission, resistance to impacts of natural hazards. The change of functional properties of an asset is referred to here as improvement. The costs of improvement intervention belong mostly to capital expenditure (CAPEX). The clear distinction between the maintenance and improvement is often not possible and perhaps not desirable. The maintenance interventions are mostly triggered by condition rating and their benefit is measured by the change in long-term maintenance costs.

For a sustainable development of societies, an unrestricted performance of terrestrial transportation networks is necessary. However, the desire to expand the network as much and as fast as possible has put pressure on both capital and maintenance/rehabilitation budgets for roads, and in many cases resulted in less resilience to sudden events.

The recent sudden failures of the Polcevera viaduct in Genoa, Italy [1], the bridge on the A60 highway in Liguria, Italy [2], Ponte di Caprigliola failure is in Toscana, Italy (Figure 1.2) and a suspension bridge in France [3], are only a several painful reminders of oncoming threats to performance of traffic networks. Lately, there have been collapses of bridges that have been only in service for a couple of decades, e.g., a bridge in Taiwan [4], which collapsed owing to a hanger failure, caused by extreme corrosion (Figure 1.2d). These reminders are fortunately quite rare, but they emphasize the need to ensure safe and reliable infrastructure, by continuous improvements of practices of road agencies towards more successful maintenance planning.

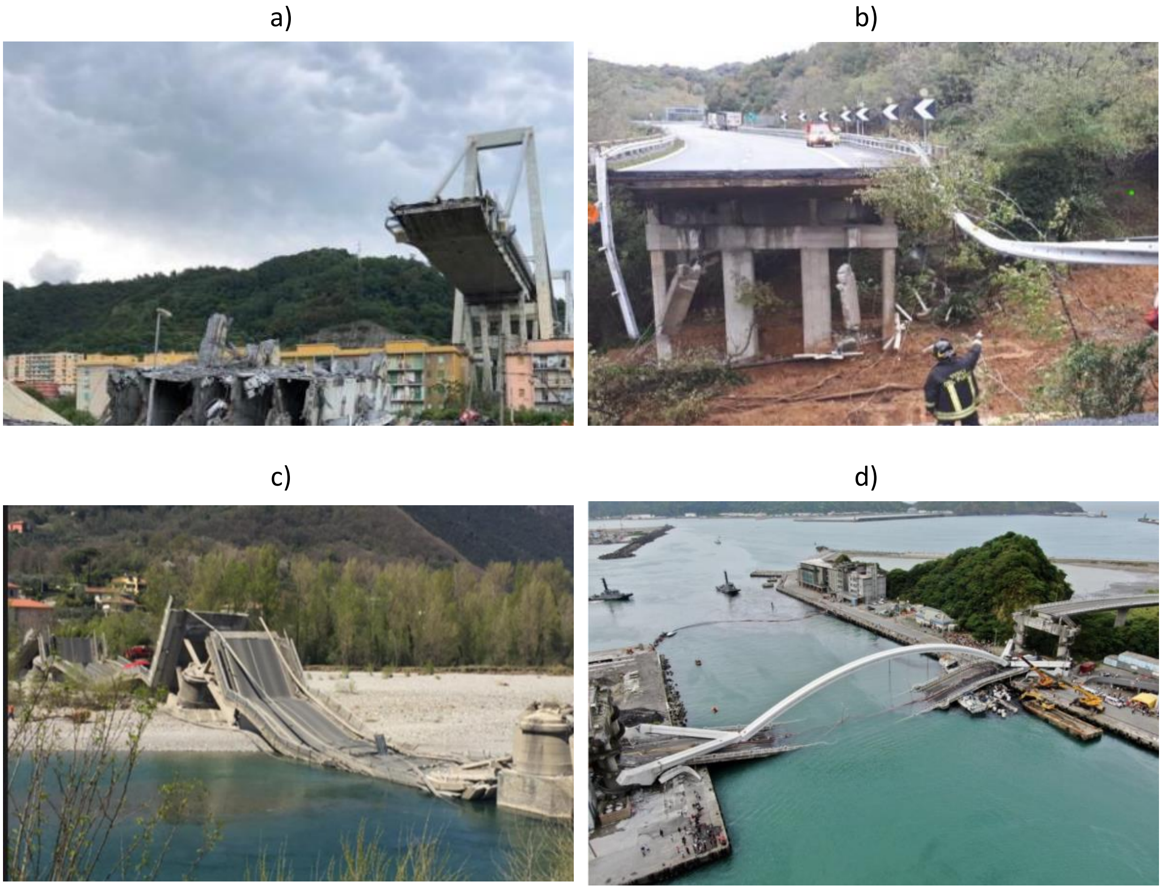


Figure 1.2 Recent bridge failures; a) Polcevera viaduct in Genoa, Italy (Aug.14 2018), @*Vigili del fuoco.tv*; b) Bridge on the A60 highway on Nov. 24 2021, Italy, @*Vigili del fuoco.tv*; c) Ponte di Caprigliola, Toscana, Italy (Apr.8 2020); d) Nanfang'ao Bridge, Yilan, Taiwan (Oct.1 2019), @CNA Photo (taiwannews.com)

1.2 Work on resilience in the previous PIARC cycle (2016-2019)

In the previous PIARC cycle (2016-2019), the Technical Committee E.1 “Adaptation strategies and resiliency”, elaborated a report: Adaptation methodologies and strategies to increase the resilience of roads to climate change – case study approach [5]. The following definition of resilience was adopted, based on [6] and [7]:

“Resilience is an ability of a system or systems to survive and thrive in the face of a complex, uncertain and ever-changing future. Resilience approach is a way of thinking about both short-term cycles and long-term trends: minimizing traffic disruptions in the face of shocks and stresses, recovering rapidly when they do occur, and adapting steadily to become better and able to thrive as conditions continue to change. Within the context of critical infrastructure, the resilience process offers a cyclical, proactive and holistic extension of risk management practices".

Thus, a resilient system should encompass the notion that the disaster resilience of society equals the society's ability to reduce

- failure probabilities of infrastructure,
- direct or indirect consequences of failures, in terms of lives lost, damage, and negative economic and social consequences, and
- time to recover (restoration of a specific system or set of systems to their "normal" level of functional performance).

The first two points relate to risk mitigation, and it should be noted that the consequences during the recovery time i.e., "reduced" level of functional performance are included in a risk assessment. Whereas there is consensus with regard to risk evaluation, the quantification of resilience is still debated. Clearly, one can quantify resilience in terms of socio-economic benefits of road infrastructure [8] and adverse event can impair this benefit until full recovery. The integral of this benefit (or disbenefit immediately after the failure) from failure to full recovery is nothing other than consequences of failure. Resilience can also be quantified in terms of functionality i.e., the ability to accommodate the traffic volume. Both quantifications express the average benefit/functionality of infrastructure over time facing occurrence rates and intensities of different hazards. There are also other, more recent resilience quantifications based on supply and demand [9], in which resilience, or rather lack thereof, is measured as percentage of uncovered demand e.g., traffic, electricity, water, gas. Disregarding these different ways of quantification, following aspects influence resilience, as discussed in [10]:

- Robustness refers to the strength or the ability of elements or systems to withstand a given level of stress or demand without suffering degradation or loss of function. Sufficiently high robustness will prevent failure and resilience will not be affected.
- Redundancy refers to the availability of substitutable elements or systems that can be activated when disruptions occur. If there is sufficient redundancy e.g., alternative routes with sufficient capacity the benefit/functionality of infrastructure and therefore resilience will not be affected. However, the rehabilitation costs need to be considered.
- Resourcefulness is the capacity to mobilize and apply material and human resources to achieve goals in the event of disruptions. Resourcefulness is a matter of careful resource planning and capacity building. If there are enough human or material resources in case of failure, recovery can proceed without any delays and hence increase resilience.
- Rapidity of response is the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption. The rapidity depends on efficient use of available resources, which shorten the recovery time and hence increase resilience.

1.3 Structure and Scope of the Report

The work on the topic of resilience was continued in the PIARC cycle (2020-2023) within Working Group 2 (WG2): Measures to improve resilience of road network. The aim of this report was to investigate and present the measures for improving each of resilience aspects: robustness, redundancy, resourcefulness and rapidity of response, using relevant case studies and lessons learned from practice. The definition of resilience was adopted from [5] and [10], while the aspect of resourcefulness is broadened to all activities of resource planning and capacity including expertise building in the prevention of failures due to an adverse event. Resourcefulness also includes the competence and ingenuity of engineering professionals in enhancing resilience. The WG2 members have suggested the cases studies and examples, which are pertinent to the experiences from their countries. It was discussed on the WG meetings, which examples are eligible to be presented and to what extent, in order to target a specific or in some cases multiple resilience aspects. The variety of presented examples allows that a broad audience of owners/operators of road infrastructure coming from low to high-income countries can relate to similar issues and learn from the experience of others.

The reader is encouraged to review Chapter 2 first, where an overview on theoretical background for quantitative resilience assessment is given. In this Chapter, the terminology used in the report and the differences and similarities between resilience and risk assessments are emphasized, with the focus on a system boundary and a value system in a resilience analysis. An overview of typical measures that increase resilience of road networks is given, which also serve as a summary of the following Chapters. Each of the Chapters 3 to 6 focus on a specific aspect of resilience with related case studies on applied measures in practice.

In Chapter 3, the measures that aim to reduce the exposure of road assets to threats are presented. These measures, which improve the robustness aspect of resilience, are discussed for the most common threats to pavements and bridges. The examples from practice show how the agencies cope with mitigation of threat scenarios by using protective/sacrificial structures and performing various environmental adaptations at micro locations where assets can be potentially exposed to threat magnitudes. The case studies elaborate on the threats coming from fire hazard in Portugal and flooding and rockfall in New Zealand.

Chapter 4 elaborates on the measures that are applied to mitigate failures of road assets which are exposed to threats. The examples from practice demonstrate common preventative activities that increase resistance of assets to expected failure modes thus aid in improving the robustness aspect of resilience. The common activities for increasing resistance of pavements and strengthening bridges in the face of threats are discussed. Further, the two case studies in this chapter present the lessons learned from the failures of bridges in flooding events in Mozambique and the performance of bridges in three earthquakes in New Zealand.

Chapter 5 covers the measures that are applied when assets cannot be viably protected or strengthened in the face of threats. On such occasions, it is good to be prepared to deal with consequences of failure(s), and a solution may be to timely increase/upgrade redundancy of road network before a threat occurs. This is demonstrated in the case of a single, critical tunnel infrastructure in Switzerland, and the case with multiple assets affected by an earthquake in New Zealand. The consequences of failure can also be mitigated if there is a possibility for a traffic modal shift (e.g., road to rail), which is shown on a simple case of a landslide in Switzerland. With the hindsight of past extreme events, the consequences of failure to network stakeholders in some cases may be reliably predicted. Thus, adequate resources can be allocated well in advance to foster a recovery phase, which is discussed on the cases of tunnels and retaining walls in Austria.

Chapter 6 elaborates on post-failure measures, which aim to reduce the recovery time and mitigate the extent of the consequences of failure(s). The targeted aspect of resilience is the rapidity of response, which is backed-up with adequate resourcefulness. It is of the upmost importance to act swiftly, especially in the case when there is low or no redundancy, which is shown in the examples of rockfall and flooding event in Canada and in the case of flooding events in Argentina and China. To enable minimum performance of a network in the case of failures, temporary solutions can be applied, which is demonstrated for the cases of failure of bridges (New Zealand) and failure of expansion joints (Austria). Application of temporary bridging structure over a work zone on a highway is shown on the case of a pilot project in Switzerland. The importance of resource planning is emphasized in the cases of earthquakes in New Zealand (human resources) and case of a flooding event in Serbia (funding).

Chapter 7 gives examples of the current agency-wide practices in road asset management, which are oriented to improving of network resilience to natural hazards. The presented approaches from the U.S. (the State of Colorado), New Zealand, Canada and Austria, highlight the significance of assessing and prioritizing maintenance projects based on resilience considerations in decision-making processes. It should be noted that the quantitative assessment of resilience discussed in Chapter 2 is not per se incorporated in the presented approaches, but they all in essence address evaluation and preservation of road network performance in the face and aftermath of threats.

The concluding Chapter 8 gives the overview of the preceding Chapters and highlights the main lessons learned. The future work on the resilience within the PIARC is also discussed.

2. RESILIENCE ASSESSMENT

2.1 Overview

It is in a common practice of road organizations to minimize risks of adverse events i.e., failures, by timely planning and executing of maintenance measures. This is an adequate approach for manifest endangering scenarios i.e., the ones that can be detected by inspections and monitoring. During inspections or by monitoring, findings e.g., damage can be recorded that allow identification of endangering scenarios and timely triggering of maintenance measures to prevent failures. The severity of endangering scenarios is expressed – depending on road organization – by a rating or a condition state, and maintenance measures are initiated before/when a condition state reaches a defined threshold. This is the essence of condition-based maintenance planning. The thresholds are chosen in such a manner to keep the probability of asset failures sufficiently low. In practice there are different flavours of condition-based decision-making so that maintenance measures are triggered by heuristic rules (e.g., [11], [12]), a threshold condition score, or more recently with criteria which are based on a set of performance indicators [13].

Unfortunately, there are threat scenarios that are sudden and don't announce themselves, so there is no ample time to prevent failures, e.g., as in a case of natural hazards. It is therefore necessary to estimate the risk due to failure(s) from such threats, i.e., their occurrence rate and related consequences. If the estimated risk is not sufficiently low, maintenance or improvement measures need to be initiated. This is the essence of risk-based decision-making. The closer look into both condition-based and risk-based decision-making reveals that fundamentally there is no difference between the two approaches – if one considers that inspections reduce the uncertainty of failure occurrence, allowing timely execution of preventative maintenance measures and hence eliminating the risk of failure.

The timely preventative maintenance mitigates the risk of failure, but the sudden failure scenarios may still occur causing instant loss of asset/network performance, indefinitely or until repairs are done. The consequences of asset failure(s) are governed by immediate losses (e.g., life and limb and material loss) but also arise and accumulate over time due to unavailability of failed assets. While traditional risk management focuses on long-term planning and reducing vulnerabilities, the resilience management puts additional emphasis on speeding up recovery and facilitating adaptation. This means that both preventative and recovery measures need to be accounted in reduction of consequences of failure(s) and risk. The consideration of recovery time is essential in estimation of resilience.

The quantification of resilience is considered to facilitate the decision making on optimal measures thus there is a need to establish an adequate framework for evaluation of resilience aspects. The goal of this chapter is to introduce the main terminology in resilience analysis, give an overview of the main considerations and existing approaches for quantification of resilience aspects, draw attention to differences and similarities to a risk analysis and provide basic understanding on measure types that improve resilience aspects.

2.2 Framework

In essence, there are overlaps between risk and resilience assessments, where the latter is considered as more comprehensive, since it additionally details the recovery scenarios and consequence analysis. A causal sequence of risk drivers: threat, failure modes and consequences of failures may be expanded with a recovery process, which altogether represent a resilience framework (Figure 2.1). Here, the scope of measure planning (medium- to long-term) is also expanded to account for contingency activities (short-term). The brief explanations of the terms in Figure 2.1 and related similarities and differences between risk and resilience approaches are given in the continuation. The possible way to quantify resilience and its aspects is presented in Section 2.2.1, while general impacts of measures on resilience are presented in Section 2.2.2. The generalized measure types to improve resilience aspects are further discussed in Section 2.3.

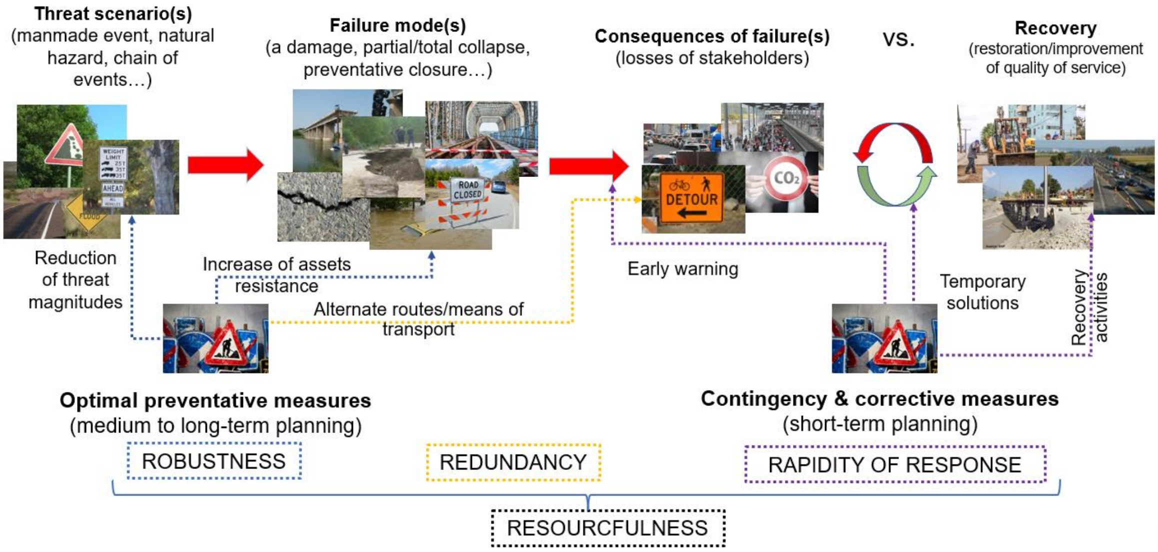


Figure 2.1 Resilience framework and related decision making on measures that improve resilience aspects of road infrastructure to threats.

Threat scenarios relate to various mutually exclusive extreme, i.e., “rare” events (or a chain of events) to which assets can be exposed with a potential to inflict serious consequences. These are in the most cases sudden events such as natural and man-made hazards, but assets can be also exposed to slow both observable and hidden processes (e.g., a gradual deterioration) or any combination of these. While the probability of simultaneous occurrence of multiple extreme events can be regarded as sufficiently low (e.g., earthquake during a flooding event), recurrent and subsequent threats (e.g., an earthquake aftershock) should be accounted for. The analysis of the latter cases is not possible using a risk-based approach, as the recovery process is not detailed unlike in a resilience analysis. Current practice is to use hazard maps (e.g., [14], [15]) to identify possible locations in the network where assets may be exposed to high magnitudes of a threat. But the geographical coincidence alone is not sufficient to initiate measures and the impact of each threat scenario must be directly associated with an asset resistance to a failure mode that can inflict consequences. By reducing exposure of assets to threats, the robustness aspect of resilience is improved. In the focus of this report are the measures for mitigation of threats coming from natural hazards and man-made events such as traffic accidents. The threats that are chosen as examples in the report are regarded as the most common and detailing on all possible threat scenarios that can impact the road infrastructure is not in the scope.

The failure modes of assets are quasi-permanent or transient situations that violate design code specifications (e.g., an ultimate limit state, serviceability limit state) or any operator/owners' provisions. The failure modes can relate to any state of an asset or its part, e.g., collapse, damage, displacement, which is inflicted by a threat and further leads to consequences (e.g., a partial or a full closure, an accident). Each failure mode of an asset is defined with two main parameters - the probability/rate of occurrence inflicted by a threat of a certain magnitude and the related severity (e.g., a damage state, a type of traffic disruption) that is essential to evaluate the pertinent consequences. To facilitate evaluation of failure modes in practice, the probability of a failure mode e.g., exceeding a damage state, for various threat magnitudes can be conveniently presented with a fragility curve. Recently, it has become a common research practice to develop fragility curves for various, generalized asset types and a specific threat e.g., see [16]. Still, the related application of such fragility curves on asset inventories for the purpose of decision-making on preventative measures is yet to be established. With respect to a threat scenario, which is defined with magnitudes at exposed assets, there can be simultaneous asset failures in a network, including both transportation and non-transportation infrastructure (see Section 2.2.1). While the probability of a such failure scenario can be rather low, the related consequences and resulting risk can be high. Special attention should be paid to the cases where failure of one asset governs the failure of other infrastructure, i.e., a cascading failure (e.g., a road bridge collapses and damages the rail track beneath). The focus of this report is to present cases from practice where the robustness aspect of resilience is improved by increasing resistance of assets to a specific failure mode from an oncoming threat.

The consequences of asset failure(s) are governed by a threat type, exposed asset types, affected stakeholders, topology of transportation networks, severity of failures and duration of recovery. The evaluation of consequences in a resilience analysis is subject to the applied system boundary and value system, which is further discussed in Section 2.2.1. The two types of consequences may be distinguished, direct and indirect. The direct consequences are those which occur simultaneously with a failure, comprising inflicted damage to infrastructure (e.g., repair/replacement costs) and loss of life and limb (e.g., injured in a bridge collapse). The indirect consequences are those which accumulate over time during the failure-triggered service disruptions (e.g., partial closure of assets, loss of electricity) and arisen circumstances (e.g., changes in user behaviour).

While the approaches for evaluation of consequences of failure in risk and resilience assessment may be regarded as similar, there are differences in consideration of consequences in these assessments. This is seen the best in the case of direct consequences. The repair/replacement costs are commonly regarded as a fixed value and directly included in a value of risk, while these costs represent the cost of recovery measures, i.e., one of (variable) parameters for which resilience is assessed. Further, the expected loss of life and limb, which is governed by a designated failure mode and a potential number of users, is regarded as a fixed value in a risk assessment (direct consequences). On the other hand, in a resilience assessment, the loss of life and limb needs to be also included via (permanent) loss or an increase in demand of services over time.

In a risk analysis, the value of indirect consequences of a failure scenario is usually estimated for a fully efficient recovery strategy – there are adequate resources to start repair/restoration of all assets and essential services at the same time, with no delays. However, the evaluation of indirect consequences over time can be complex and includes many uncertainties, becoming cumbersome to include in a risk analysis, especially when there are several assets which can fail simultaneously in a threat scenario. Further complications emerge if repairs are delayed (e.g., due to a resource shortage), performed over several years and/or coincide with previously planned maintenance activities. There could also be a case when a recovery process is impeded with another threat scenario. A resilience analysis can account for such and similar cases giving an insight on how the recovery process unfolds i.e., how is the loss of service restored. With respect to consequences of failures, the focus of this report is to both investigate adequate measures that can be applied well in advance of a threat occurrence and after the failure had already occurred, with a main goal to minimize the consequences thus improve resilience.

The recovery is related to the restoration/improvement of asset(s) after failure(s) had occurred and it is a unique aspect to the resilience analysis, not detailed in a risk analysis. Essential for the recovery phase is to be aware of various circumstances that may be preventing related activities to commence and/or impede their efficiency, thus prolong the recovery duration:

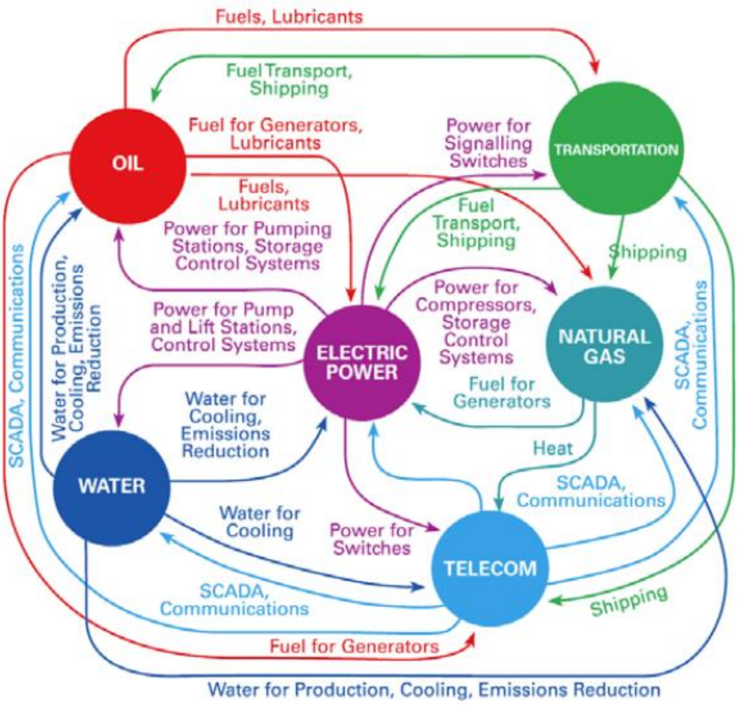
- Lack of resources (e.g., funds, manpower, machinery),
- Increased demand on critical services (e.g., obstructed lifelines, many injured)
- Slow-receding or a recurring threat magnitude (e.g., in flooding, earthquake),
- Failure(s) of non-transportation infrastructure (e.g., power, water supply)
- Poor prioritization (e.g., saving/relocating people vs. restoration of services)
- Inflexible legislation (e.g., a long tendering procedure),
- Challenging inspection circumstances to ascertain damage severity (e.g., due to debris), and
- Any combination of the above listed

After failures occur, the assets either remain fully closed until repaired or with impeded functionality (e.g., one lane closed, speed/weight restriction). The recovery phase may imply temporary solutions (e.g., instalment of a pontoon bridge, traffic rerouting), that would enable minimum (i.e., essential) operating capability for stakeholders (e.g., see [17]) and thus reduce the build-up of consequences. It the scope of the report are measures which aim to contain the extent of consequences of failure and measures that restore transportation services to the state before the failure(s) had occurred.

2.2.1. Quantification of Resilience Aspects

The framework for resilience assessment is entirely dependent on the adopted system boundary and the value system. The system boundary specifies the scope and detail of an assessment while a value system is focused on the metrics for evaluation of the benefit generated by an investigated transportation network.

With respect to the system boundary, a threat scenario can cause one failure or more simultaneous asset failures that can emanate consequences to the community as a whole, impacting not just transportation but also energy, communication and other services (Figure 2.2). Different stakeholders can be affected (Table 2.1) due to the cascading impacts of a failure to other transportation networks and critical services. The scope of a resilience analysis may also include impacts of predefined maintenance strategies and/or a successive threat event(s) hindering the recovery phase of an occurred failure.



(***SCADA** - Supervisory control and data acquisition system)

Figure 2.2 An example of connections and interdependencies across economy, [18].

Table 2.1 An example of a road stakeholder list for a resilience assessment, [19].

Stakeholder group	Definition	Examples
Owner/manager	Entity responsible for decisions with respect to physically modifying the infrastructure	A road authority, a concessionaire
Users	Persons who are using the roads	A person being transported on a road, a person transporting something on a road
Directly affected public	Persons who are in the vicinity of the road but are not using it	A person in a house next to the road that hear vehicles driving on the road, a person working at a gas station near a road
Indirectly affected public	Persons who are not in the vicinity of the road but are affected by its use	A person in a house far away from the road that do not hear vehicles driving on the road, but are affected by changing climate due to the emissions produced by vehicles using the road

A value system can be defined as a coherent set of established values, norms or goals adopted and/or evolved by a person, organization or society as a standard to guide its behaviour in preferences in all situations. In this case, a value system needs to account for the demands and priorities of stakeholders related to road infrastructure. These demands and priorities can be mirrored to asset management objectives relating to the quality of service (i.e., fitness for purpose) of infrastructure over time. In fact, the aspects of resilience – robustness, redundancy, resourcefulness and rapidity of response, can be represented via a set of asset management objectives, which are defined on a network level for a case of normal operation and the case of threat scenario of a certain magnitude.

As investigated recently in the PIARC report [20], road agencies are on route or already assessing asset management objectives by a set of Key Performance Indicators (KPI), e.g., [13], [21], [22], [23], [24]. The KPI can be understood as technical parameters that define quality of service, and which can be easily communicated to the stakeholders. The KPI can be assessed/evaluated via one or more performance indicators (PI), which may be qualitative or quantitative values. The following KPI groups are most commonly used (the pertinent PI are in brackets):

- Condition of infrastructure (e.g., condition state, probability of a structural failure),
- Mobility of users (e.g., travel time, travel distance),
- Safety and comfort of users (e.g., loss of life and limb, accident rate),
- Environmental impact (e.g., water pollutants, greenhouse gasses), and
- Socio-Economy (e.g., noise level, fuel costs, vehicle maintenance, perishable goods)

To meet the asset management objectives, the extremizing or satisfying criteria can be set for the KPIs. The result of meeting the asset management objectives generates benefit to stakeholders. The nominal value of this benefit may be e.g., related to mobility of users and the pertinent KPI – travel time. For example, if a bridge is not available, the related traffic is rerouted, which causes an increase of travel time of all vehicles throughout a network. The difference between the travel times in the case of normal bridge operation and in the case of reduced functionality can be understood as a loss of benefit which the bridge normally generates. Further, the inflicted consequences of a bridge failure may also comprise loss of life and limb, environmental, social, economic, political and other consequences.

An example of a benefit measurement related to road users and possibilities for monetization is given in Table 2.2. If all consequences (i.e., their KPI) of failure can be monetized, the loss of benefit due to infrastructure failure in a sudden event could be normalized. One of the difficulties lays in monetization of non-monetary KPI (e.g., life loss, delays, noise impact, air/water pollution), where it is necessary to have information i.e., studies on pertinent unit costs, e.g., as in [25], for life-loss [26] and for traffic and environment. The KPI related to the safety and comfort of users may be monetized via the number of people who are injured in a failure mode (e.g., based on a statistics) and via the costs of additional number of accidents which occur due to additional driving distance of the road users. The KPI of socio-economy and environmental impacts usually have a basis for monetization in additional driving time/distance of road users [27]. Alternatively, for some non-monetary KPIs such are those related to user/client satisfaction or comfort and ecology, a "willingness to pay" approach could give an estimate on the corresponding monetary value.

Disruptions in the transportation network due to natural or man-made threats can have wide-spread impacts on the movement of goods and provision of services e.g., healthcare and electricity. This can result in serious stalling of physical and economic recovery. Therefore, it is critical that a rapid recovery from a disaster is planned and executed prudently. Figure 2.3 shows an example of a temporal and resource demand for a recovery planning. Initially, the planning typically focuses on short-term response activities to restore access to cut-off locations and provide minimum (i.e., essential) operating capability (MOC) for affected stakeholders. Longer-term recovery planning focuses on achieving a minimum sustainable capability (MSC) and eventually the full recovery (i.e., routine performance). The times t_1 and t_2 in Figure 2.3 denotes the times until the stakeholders can tolerate the performance levels under the MOC and MSC, respectively.

Table 2.2 Measures of benefit (service) related to road users, [19].

Label	Description	Category	Category description	Assessment
Travel time	Impact of travel condition in terms of time lost in travel	Work	Economic impact of wasting work time travelling	Salaries of the persons travelling
		Leisure	Economic impact of wasting leisure time travelling	Willingness to pay to reduce travel time
		Commuting	Economic impact of delay during commuting travel	Willingness to pay to reduce travel time
Accident	Impact on the users due to the users being involved in an accident	Property damage	Economic impact of repairing the vehicle	Cost of replacing the damaged property or as part of the fatality or injury costs
		Injury	Societal impact due to the injury	Willingness to pay to avoid injury
		Fatality	Societal impact due to the fatality	Willingness o to pay to avoid fatalities
Vehicle operation	Impact on the vehicle cost	Operation	Economic impact of people ensuring that fuel and oil is available for use	Cost of fuel and oil
		Maintenance	Economic impact of people repairing vehicles and ensuring that materials, e.g., tires and brake pads, are available for use	Costs of vehicle maintenance
Comfort	Impact of travelling on the users	Physical	Societal impact of obtaining for example, bruises from an extremely bumpy ride	Willingness to pay to reduce the physical effects of the ride, such as noise or vibration
		Psycho-Logical	Societal impact of having for example, anxiety due to a perceived increase in the probability of being involved in an accident, or of seeing things while travelling	Willingness to pay to reduce the psychological effects of the ride
Noise	Societal impact due to the users coming in contact with sound emissions			Willingness to pay to reduce noise

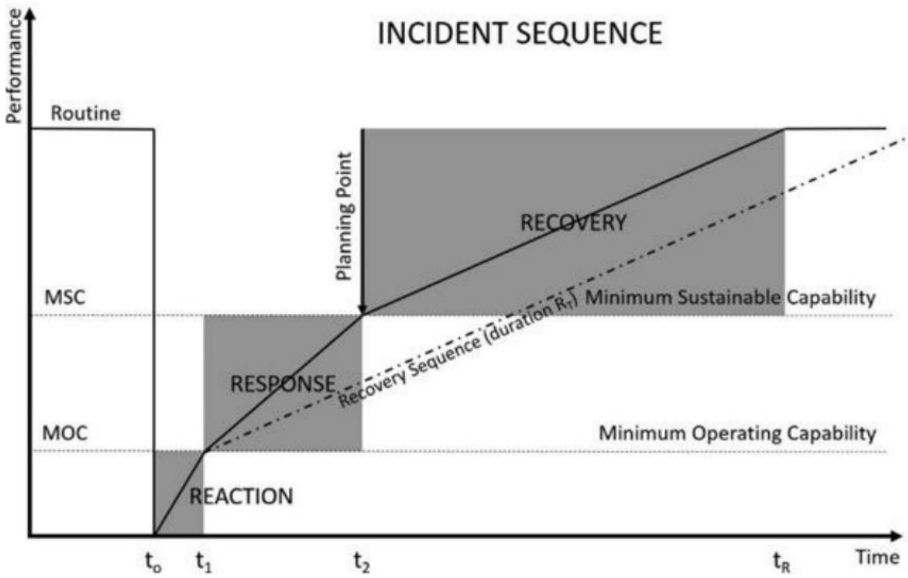


Figure 2.3 An incident sequence with resource burden vs. performance over time, adapted from [17].

The list of essential services for stakeholders can be lengthy and may differ for countries around the world. For example, restoration of heating capacity would be an essential service in lands that experience harsh winters, while restoration of air conditioning would be just as critical in countries that experience high temperatures in summer. A list of essential services is provided below:

- health care and social services,
- utilities such as water, electricity, natural gas, oil, sewage treatment and disposal, etc.,
- transportation services provided by air, water, road and rail,
- transportation support services including logistics, fuelling, maintenance and repairs, etc.,
- food production and distribution,
- policing and law enforcement, fire and emergency services, paramedic services, and
- telecommunication and information technology services.

All of these services utilize transportation infrastructure such as roads and bridges to deliver their services. One of the difficulties in recovery planning is defining the MOC and MSC performance levels (Figure 2.3). For example, a bridge that is washed away by a flood, can cut-off a community from a road network, considerably limiting its access to resources and services. While other modes of delivery such as air or water may be possible, these may not be the most desirable due to quantity restrictions, timing and costs. The full restoration of the bridge may take months or even years to complete and the provision of a temporary structure, which can be installed in matter of days, may not have the capacity to completely restore the function of the original bridge. However, the temporary solution may provide access for vehicles with lower load carrying capacity, which may satisfy the MOC as shown in Figure 2.3. The performance criteria in post-event situation can be developed for specific stakeholders and critical infrastructure as shown in Table 2.3.

Table 2.3 Example performance criteria in a post-event situation, [28].

Service provided	Priority/criticality of relevant road link	Level of service	Measure
1a. Temporary access to emergency services for emergency service vehicles	Very high	Restore temporary road access to hospitals and emergency centres.	Within two hours
1b. Temporary access to emergency services for emergency service vehicles	High	Restore temporary road access to hospitals and emergency centres identified by the district health board	Within two days
2a. Access to lifeline utilities	N/A (all are assumed equal)	Restore 4x4 road access to power, water and telecommunication utilities for inspection and repair.	Within three days.
3a. Network availability	High	Re-open one lane for heavy trucks and buses	Within 24 hrs.
3b. Network availability	Medium	Re-open one lane for heavy trucks and buses	Within 36 hrs.
3c. Network availability	Low	Re-open one lane for heavy trucks and buses	Within one week

With respect to the previous considerations in this Section, the resilience (Re) can be understood as a measure of average long-term benefit B(t) from transportation network on an analysed interval. In Figure 2.4 the benefit is normalized (max. value =1.0). When a sudden event of certain magnitude occurs, it may lead to asset failures. This is represented with the loss of normalized benefit starting in the time t_{event} until the onset of the repairs (t_{rep}), where it has dropped to the value B_{min}. The shape (i.e., the drop) of this part of the benefit curve is governed by the robustness and redundancy aspects of the affected network and assets within. The time from t_{rep} to t_{rec} is the recovery period in which the functionality of the analysed network is being restored to the level prior the event. The rapidity of response aspect governs this recovery of normalized benefit as well as the duration of the repair delay (t_{event}-t_{rep}). The shaded area in Figure 2.4 below the curve of normalized benefit, gives the value of resilience on the analysed interval.

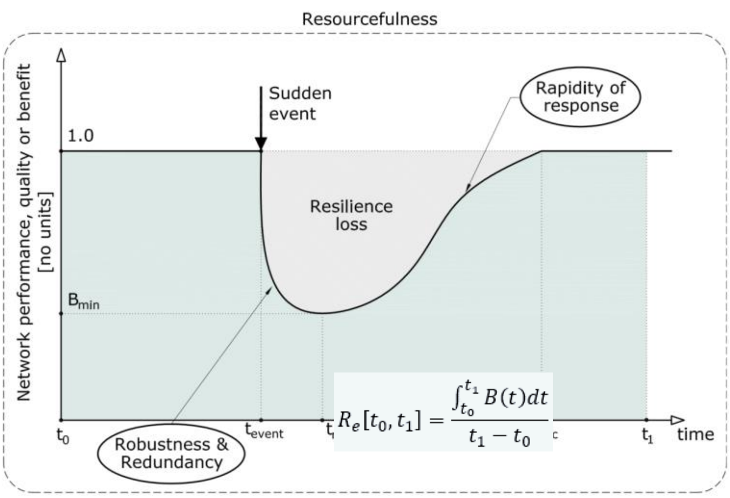


Figure 2.4 Principle of evaluation of resilience based on a normalized benefit generated from infrastructure.

It is common in research and practice to refer to the resourcefulness aspect only in a recovery phase, but in fact the underlying resource and capacity management as well as engineering competence can be related to all resilience aspects. So, the resourcefulness governs both loss and recovery of the benefit, [29].

When establishing a system boundary and a value system in a resilience analysis, it is essential to identify critical assets, i.e., those which failures (or a specific combination of failures) have a potential to generate the highest consequences. For example, this can be related to the part of a network which have no redundancy i.e., where the essential services to stakeholders can be completely cut-off due to just one asset failure. So, the referent value of normalized benefit today (i.e., a value of 1.0 on the y-axis in Figure 2.4) need to correspond to the most pessimistic, but probable threat/failure scenario. One should bear in mind that the demand(s) of stakeholders i.e., the value generated via infrastructure today can also increase/decrease over time due to population migration, traffic variation, climate change, technological advancements (e.g., use of electric cars), or due to a future planned activity which directly increase/decrease network redundancy (e.g., building of alternative routes, bridges), etc. The permanent loss or shift of demand for some services can also occur due to a considerable casualties/wounded or severely destroyed infrastructure. Similarly, population relocation (e.g., to emergency shelters), resource conservation measures (e.g., potable water saving measures), can affect the demand for resources as discussed in [30]. To account for such circumstances, there is a need to expand the system boundary and adapt the value system in the evaluation of benefit from infrastructure.

2.2.2. Quantifying the impact of measures on resilience improvement

A slow deterioration process may cause damage to assets that compromise their performance (e.g., a steel corrosion). However, such processes usually leave ample time for adequate maintenance planning and execution. While some damage do not directly endanger functionality or structural safety of assets, these may severely reduce resistance of assets to oncoming sudden threats. An example would be deterioration of bearings on a bridge. In a case of normal operation i.e., predominantly vertical loads from traffic, the bearings performance may not be compromised over time but in a case of an earthquake, the bearings perhaps would not perform as designed. Such and similar cases need to be identified, so a timely and adequate preventative maintenance may be executed (Section 2.3). Depending on asset and maintenance type, there might be a planned and purely administrative reduction of asset functionality until the works are completed.

Taking into account Figure 2.4, the impact of preventative maintenance on resilience improvement is presented in a following example (Figure 2.5). The threat to network performance may come from a sudden event such is an earthquake, which can happen anytime in the future, affecting bridges in the network. Due to a slow deterioration process (e.g., corrosion), one of the bridges in the network may become more prone to a failure in an oncoming earthquake. This happens as the strength of one of the bridge bearings to horizontal loads is compromised (S_{max} drops to S_{event} in Figure 2.5). If there is no adequate maintenance, the related bridge will fail in an earthquake leading to reduced network performance (from B_{max} to B_{min}) until recovery is initiated in t_{rep}. The return of the network to the pre-failure state may last for a long time (t_{rec}). However, if a preventative maintenance is performed before the earthquake occurs (e.g., from t_a to t_b), it would imply a short, minor traffic disruption, but also have a considerable impact on the network resilience when a threat eventually occurs (the dashed orange lines in Figure 2.5). Ideally, there would be minor damage and the traffic could be fully restored after a rapid inspection/intervention.

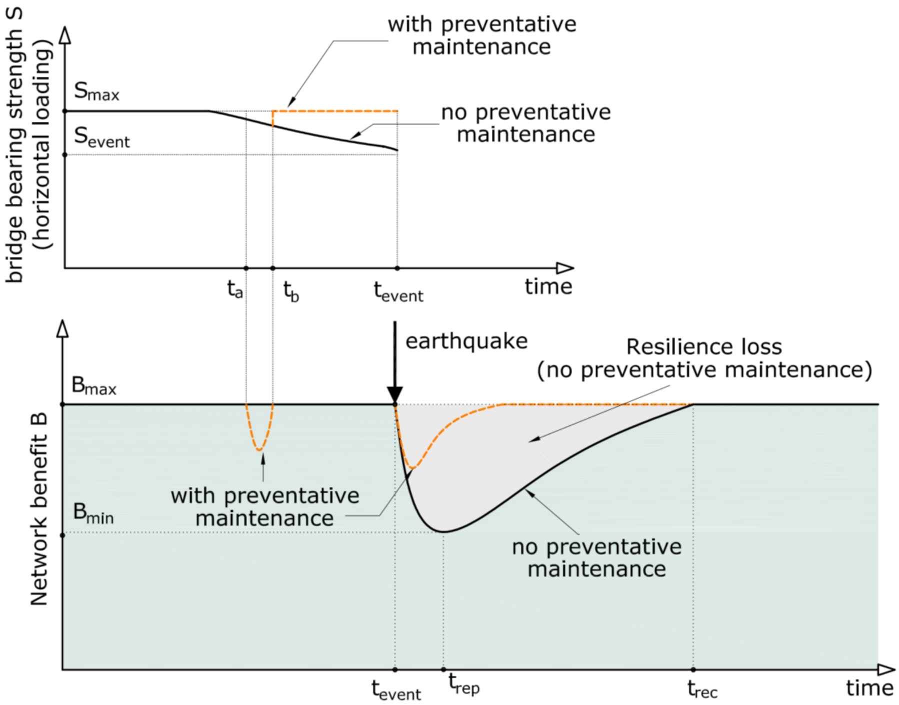


Figure 2.5 An impact of preventative measure on resilience improvement.

The impact of response and recovery measures (see Section 2.3) on resilience improvement is presented in the following example, where network functionality is taken as the governing parameter to measure network benefit and consequently the resilience (Figure 2.6). In a general case, a loss of network functionality due to failure(s) may not occur instantly, and also an adequate response/recovery may start with a delay. Ideally, prudent planning of response measures should have a positive impact on restoration of functionality F to the network state before failures (F_{max}) and the recovery time ($t_{recovered}$) as schematically presented in Figure 2.6. Here, the t_{event} denotes the moment of failure occurrence, t_{Fmn} the time when default (reference) recovery measures are to be initiated, accounting for available resourcefulness (the Impact phase). Until the recovery measures are initiated, the network functionality drops to the F_{min} value. The t_{delay} represents the time when optimal measures should be initiated to maximise the resilience (red-dashed and blue-dotted line), with available resources.

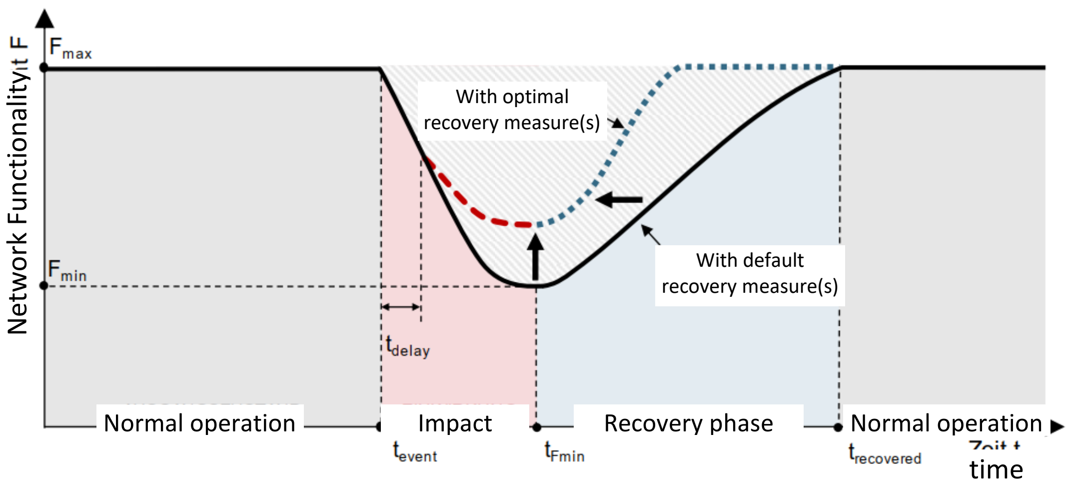


Figure 2.6 An impact of an optimal recovery measure on resilience improvement, adapted from [31].

2.3 THE SCOPE OF MEASURES THAT IMPROVE RESILIENCE ASPECTS

The decision-making on optimal measures for road assets in the face of threats considers two approaches:

- Medium to long-term planning, which focuses on a preventative maintenance to mitigate threats, related failures and potential consequences, that can occur anytime in lifetime of assets, and
- Short-term planning, which focuses on execution of response & recovery activities for failures that are about to happen or have already occurred.

The two main aims of preventative maintenance are reducing exposure of assets to threats and preservation of physical integrity & serviceability of assets and user safety in a case of a threat occurrence. These aims are related to increasing the robustness aspect of resilience. Also, measures may be planned well in advance to aid in mitigation of potential consequences of failures, and these are related to increasing the redundancy aspect of resilience. On the other hand, response & recovery activities mainly target restoration and adaptation back to the pre-failure state and alleviation of the consequences of occurred failure(s), which is related to the rapidity of response aspect of resilience. It should be noted that there are also activities (medium to long-term) that imply increasing the capacity of human and material resources, which are crucial for decision making. These activities are performed to increase both efficacy and effectiveness of all above-mentioned measures and are in fact related to increasing of the resourcefulness aspect of resilience.

The overview of generalized measures and activities that can improve resilience aspects are presented in Table 2.4. If necessary, the maintenance measures can be related to one or more assets and may be combined as well, for an optimal maintenance strategy for a road network. The optimal scope and schedule for application of measures is depending on various circumstances: threat type, asset type and exposure, vulnerability of a network to failure of multiple assets, available resources, etc. It should be noted that an execution of measures can be understood as “a planned failure state” of an asset and related network, as these may temporarily reduce the functionality of the asset and the network on the whole. The approach for mitigation of the consequences of the planned maintenance to stakeholders usually involve just administrative measures. It should be kept in mind that a planned maintenance campaign makes the network more vulnerable to sudden threats, and this impact on network performance needs to be accounted in the resilience assessment as well (e.g., see Figure 2.5), to find the optimum maintenance schedule.

Preventative measures may have a cascading impact on resilience aspects, e.g., a measure that increases robustness may have a positive effect on a rapidity of response. For example, a strengthening of an asset mitigates a failure mode occurrence but also reduces the damage severity in a case of an eventual failure, allowing for a swift and economic repair. Also, it should be noted that applying a measure on one asset may create unfavourable circumstances to other assets, which may be accounted as a probable threat scenario. For example, planting vegetation to prevent soil erosion may cause a clogging of a drainage system in a flooding event, causing a cascading threat to various stakeholders. This cascading impact of measures is not treated in the report.

Table 2.4 The general type of measures/activities to improve resilience

Resilience aspect	Measure scope	Measure/activity type
Robustness	Reduction of exposure to threats (Chapter 3)	- installation/upgrade of protective (sacrificial) structures - environmental adaptations at asset micro-locations
	Increase of asset resistance to failures (Chapter 4)	- enhancing properties of asset and its elements - controlling/triggering desired failure mode
Redundancy	Mitigation of consequences of failures (Chapter 5)	- building alternate routes with adequate capacity - increase of traffic mode interchangeability - installing back-up systems for non-transportation infrastructure (power/water supply)
Resourcefulness	Increasing the capacity of resources (Chapters 3 to 7)	- the capacity to identify problems, elaborate innovative and judicious solutions, expertise of the personal involved. - prudent allocation of emergency budget, manpower and machinery - response planning that fosters simultaneous repairs of several assets - temporary structures or structural elements to provide at least minimum operational network performance
Rapidity of response	Mitigation of consequences of failures & Recovery (Chapters 5, 6)	- efficient repair/rebuild activity planning (prioritization) - continuous training and improvements of the response teams - swift legal response (emergency budgeting)

It is implied that the preventative measures for assets will be effective provided regular, periodic maintenance is duly performed (e.g., use of de-icing salts), the state of the protective structures satisfactory (e.g., drainage unclogged, debris removed) and equipment is operational (e.g., a water pumping station). If this is not the case, a threat magnitude may cause more issues than originally anticipated, leading to cascading failure scenarios with severe consequences (e.g., one clogged drainage causes closure of multiple road sections). The detailed investigation on periodic maintenance measures, condition of protective structures, equipment redundancy, and their impact on resilience are out of the scope of this report. Administrative measures in the face and in the aftermath of a threat, which are aimed at e.g., traffic restrictions, indeed can impact the recovery process but are not investigated in this report.

Monitoring with instrumentation or a visual inspection may be regarded as a cost-effective measure in the face of various threats, which improves resourcefulness aspect of resilience i.e., increases the capacity to identify and solve problems. For slow observable/hidden processes (e.g., a corrosion in a pre-stress cable), monitoring/inspection has aim is to trigger timely, preventative mitigation measure(s). On the other hand, for sudden processes, monitoring can be used for early warning (e.g., inclinometers for monitoring slope and rock stability, remote satellite sensing, video-based surveillance, motion sensors) to mitigate short-term consequences of failures, by triggering administrative measures (e.g., traffic rerouting) and emergency team response. Also, during an event and in the aftermath of an event, monitoring solutions (e.g., surveillance with drones) may be used in restoration planning/execution phase. Detailing on the monitoring/inspection solutions was out of the scope of this report.

3. REDUCTION OF EXPOSURE OF ROAD ASSETS TO THREATS

3.1 OVERVIEW

The preventative measures, which are applied towards reduction of exposure of road assets to threats, are primarily aimed at the improvement of robustness aspect of resilience of road networks. In general, it is not possible to fully eliminate a threat, but the efforts are made to considerably decrease threat magnitudes/frequency at asset micro locations, and thus mitigate failures. One approach to significantly absorb/deflect threat magnitude is via protection i.e., sacrificial structures (e.g., rock fences). In some cases, it is viable to consider environmental adaptation of micro-location of exposed assets e.g., by cutting vegetation, river channel management, soil conditioning, etc. The efforts of road agencies to identify relevant threat scenarios where assets may be exposed and elaborate optimal solutions to reduce oncoming threat magnitudes are in this report considered as improvements to the resourcefulness aspect of resilience. The distinction is made to the measures that are related to permanent modification of asset properties (e.g., applying protective coatings) and installation of various electro-mechanical equipment (e.g., seismic dampers) or other add-ons, which may be considered as an integral part of exposed assets. Such and similar measures that are mainly aimed to improve the resistance and/or response of an asset to occurred threat magnitude are in the scope of Chapter 4.

In this chapter, a general review of measures for threat reduction to preserve pavement infrastructure and bridges are given. Further, several case studies are selected as examples of best practices in dealing with reduction of exposure of road assets to wildfires (Portugal), flooding and rockfall (New Zealand).

3.2 PROTECTION OF ROAD INFRASTRUCTURE

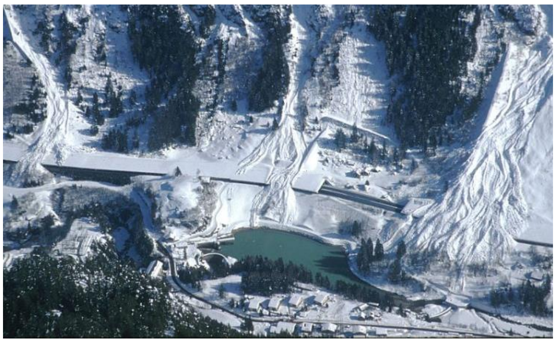
An example of a threat mitigation by a protective structure is an alpine debris torrent structure (Figure 3.1a). These structures are in essence a dam constructed in the mountain valley up slope of a road. Such structures are located in areas where heavy rains typically erode the mountain face and carry debris downstream. Against avalanches, galleries (Figure 3.1b) and various protective fences may be effective (Figure 3.1c). The protective structures are monitored annually and after all major natural events inspected and scheduled for debris removal in the face of future events. More solutions for protection from debris/rockfall is given in the case study in Section 3.3.3.

The exposure of all road infrastructure to flood magnitudes can be significantly reduced by hydraulic countermeasures and/or biotechnical countermeasures, e.g., see [32] and [33]. In the light of the adopted classification in Table 2.4, such measures are regarded as environmental adaptations at asset micro locations (Figure 3.2). The hydraulic countermeasures imply “river training” structures, which primarily modify water flow, such are embankments, transverse dikes, guide banks, sediment detention basins, etc. Biotechnical countermeasures are mainly used to control streambank erosion or as a bank stabilizer. These measures imply vegetated geosynthetic products, woody mats, vegetated riprap, root wads, live staking and similar. Purely biological countermeasures include forestation of the areas that are deemed prone to debris/avalanche (e.g., an avalanche forest).

Control of water levels and drainage in some cases may be done via water pumping stations. Large amounts of precipitation often occur at times when there is an increased probability of a power failure, thus pumps should be designed redundant to avoid the risk of technical failures.

a)

b)



c)

Figure 3.1 Examples of protective structures. a) alpine debris torrent structure, Sea to Sky Highway, Canada, ©BCMoTI; b) avalanche gallery, Switzerland, @ASTRA; c) avalanche gallery with horizontal wooden beams, Austria, ©ASFINAG;.

a)

b)

c)

Figure 3.2 Examples of hydraulic and biotechnical countermeasures. a) small bed load barrier, ©ASFINAG; b) a diversion channel, [34]; c) a geo-mesh for lining riverbanks, [34].

3.2.1. Pavements

In general, pavements can be exposed to an excess or a lack of moisture and changes in temperature, resulting in various damage that cause unpleasant/dangerous driving conditions. For the cases where these threats are not sudden and can be anticipated, the potential damage thereof may be intercepted by a timely mitigation action (e.g., with a regular maintenance). Timely maintenance is enabled by judicious monitoring, which is related to resourcefulness aspect of resilience. It should be noted that treatments on pavement that relate to regular maintenance or have a temporary effect (e.g., de-icing salt) are considered as a threat mitigation activity, while those with a permanent effect (e.g., coatings) are considered to increase resistance of pavement to damaging actions of a threat magnitude and discussed further in Chapter 4 (see Table 4.1). The most common threats, potential failure modes and threat mitigation measures are summarized in Table 3.1. In Figure 3.3, Figure 3.4 and Figure 3.5, a selection of common pavement damage due to various threats is given.

Table 3.1 Protection of pavements by threat mitigation (1/2)

Threat	Potential damage/failure state	Threat (exposure) mitigation measure
Increase in average/ maximum air temperature & heatwaves	Pavement surface rutting, flushing and bleeding (due to reduction in asphalt binder stiffness) (Figure 3.3a,b).	Cooling of pavement by spraying water with trucks; (an alternative measure is increasing resistance of pavements to heat, see Table 4.1).
	High deformation under stress (due to lower asphalt concrete dynamic modulus).	
	Spalling and blow-up of concrete slabs (curling and warping effect due to thermal expansion) (Figure 3.3c, d).	
Reduction in frost depth penetration	"Frost heaving" - upwards soil swelling resulting in reduced bearing capacity of pavements (Figure 3.4a).	Upgrade of a drainage system; Keeping the outlets free from debris (i.e., updating the schedule of regular maintenance).
Decrease in frequency of very cold days	„Fatigue cracking“ due to increased stress on the surfaces that would typically stay frozen longer due to insulating effect of snow (Figure 3.4c).	No viable measure for direct reduction of exposure; (an alternative measure is increasing resistance of pavements to water ingress, see Table 4.1).
Reduction in snowfall	Ravelling and potholing due to excess water (Figure 3.4b).	Maintenance of pavement and shoulder cross-slopes to ensure timely water drainage of a pavement surface.
Increased frequency of freeze/thaw cycles	Scaling of concrete surfaces (Figure 3.4d).	Providing adequate transverse and longitudinal drainage of pavement surfaces.
	Potholes resulting from increased stress on asphalt binder/aggregate adhesion.	
	Higher frequency of potholes for both flexible and rigid pavements.	No viable measure for reduction of exposure.

Threat	Potential damage/failure state	Threat (exposure) mitigation measure
	Decreased bearing capacity and other defects resulting from water ingress through cracks (Figure 3.4c).	Maintenance of pavement and shoulder cross-slopes to ensure any water of the pavement surface is drained off the pavement in a timely fashion.

Table 3.1 Protection of pavements by threat mitigation (2/2)

Threat	Potential damage/failure state	Threat (exposure) mitigation measure
Increased frequency of ice events	Potholes for distressed pavements (flexible and rigid); Slippery surfaces.	Use of various de-icing chemicals, sands and treatment procedures (adapting regular winter maintenance schedule).
Increased frequency of rainfall events	Excess water on pavement surface (Figure 3.4b).	Upgrade of stormwater infrastructure; (an alternative measure is increasing resistance of pavements to water ingress, see Table 4.1).
	Joint faulting in concrete pavements (erosion caused by pumping of a trapped water under a concrete pavement).	
Changes in groundwater level	Cracking of a subgrade and pavement (lower levels of water); Reduction of the bearing capacity of a subgrade (higher levels of water). (Figure 3.5b).	Provision of additional drainage such as subdrains, deepening ditches, etc.
Increased intensity rainfall	Excess water on pavement surface.	Upgrade of stormwater infrastructure; (an alternative measure is increasing resistance of pavements to these circumstances, see Table 4.1).
	Slope and granular shoulder erosion (Figure 3.5a**).**	Using vegetation or other means to mitigate erosion of earth slopes; Sandy granular base and subbase materials may require stabilization and use of asphalt sealers.
Drought conditions	Shrinkage cracking of asphalt and concrete (clay and silty clay subgrade).	Conditioning of subgrade soils very close to its optimum moisture content; Stabilizing soils by treating them with lime, cement or other additives, or by conditioning the soils to a consistent moisture content and encapsulating a portion of the soil in heavy duty polyethene.
	Differential settlement, increased pavement roughness and cracking of concrete pavements (due to post-compaction volume changes in subgrade & granular layers).	No mitigation measures known at this time.

Flooding	Pavement rutting, asphalt fatigue cracking and concrete slab cracking (depending on the duration of flooding).	Upgrade of stormwater infrastructure; Hydraulic/biotechnical countermeasures (see Figure 3.2 and Section 3.3.2).
	Slow receding of water (e.g., due to sediment clogging of the open graded drainage layers and other stormwater infrastructure).	
	Washing away (Figure 3.5a).	
Wildfire	Various damage to pavement.	Roadside vegetation management (see Section 3.3.1).
Landslides; Rockfall; Avalanche	Various damage to pavement	Protective/sacrificial structures (see Figure 3.1 and Section 3.3.3).

Figure 3.3 Common pavement damage due to temperature changes. a) asphalt surface rutting; b) asphalt surface flushing; c) loss of pre-formed neoprene joint sealing (a rapid cooling event); d) spalling of concrete slabs (thermal expansion); ©Hein, D.

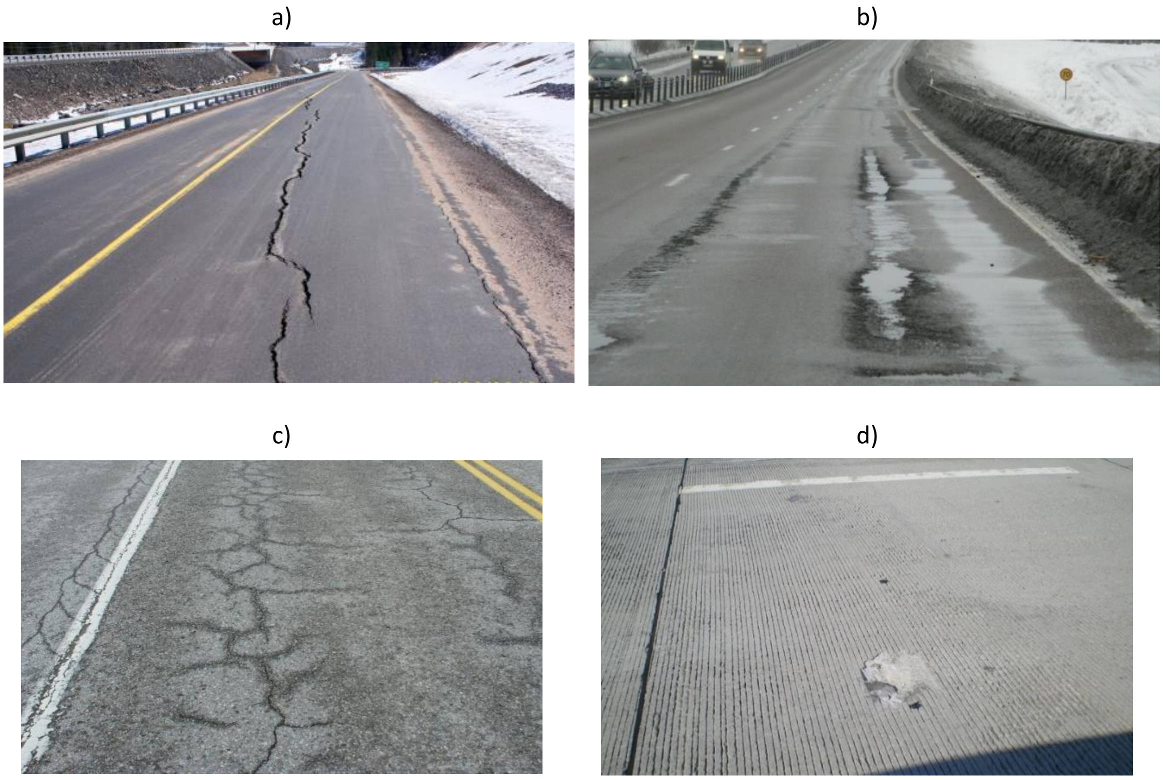


Figure 3.4 Common pavement damage related to freeze/thaw process; a) an impact of frost heaving; b) ravelling and potholing; c) fatigue cracking; d) concrete slab scaling; ©Hein, D.

a) b)

Figure 3.5 Common pavement damage due to excess water ingress. a) shoulder erosion on a highway; b) failure under load of construction equipment; ©Hein, D.

Also, it should be noted that some threats can have a positive effect on roadways, which should be taken into account in periodical and preventive maintenance planning (Table 3.2).

Table 3.2 Threats and potential benefits for pavements

Threat	Potential benefits
Increase in average temperature	- Lengthening of a construction season, - Reduction in frequency of snow and ice events, - Reduction of freeze/thaw cycles, and - Reduction in concrete pavement joint opening width, which increases load transfer from one slab to another.
Increase in maximum temperature	- Reduction in snow depth during snow events, - Reduction in need for winter salt and sand, and - Increased time for asphalt concrete compaction.
Reduction in frost depth penetration	- Reduction in the potential for frost heaving
Decrease in frequency of very cold days	- Reduction of scaling of concrete surfaces, - Potential reduction of low-temperature cracking, and - Reduction of stress on asphalt cement binder (rutting, flushing, bleeding).
Reduction in snowfall	- Reduced maintenance for snow removal
Changes in groundwater level	- Lower groundwater level will reduce moisture content of a subgrade and can increase bearing capacity of pavements.
Increased drought conditions	- Dryer pavement and subgrade layers may increase the bearing capacity of pavements.

3.2.2. Bridges

During a flood event bridges may be affected by one or a combination of actions: soil erosion (e.g., local scour at substructures, undercutting of bridge approaches), debris impact, water uplift and overtopping. Each of these actions may lead to a failure mode, thus estimation of optimal mitigation measure(s) should be done on a case basis. The hydraulic measures (e.g., Figure 3.2) can be applied at bridge sites to reduce magnitudes/frequency of overtopping, which is exemplified in the case study in Section 3.3.2. Commonly applied are "armouring" measures, which do not reduce the initial threat action (i.e., height of water or magnitude of a flow at bridge substructures), but they lower the potential of a consequent process i.e., (local) scour that may eventually lead to failures. If the armouring measures are related to altering/enhancing geometry of substructures and their foundations (e.g., gabion pile at piers), they are classified in this report as measures that increase resistance of a bridge in a flooding event (Section 4.2.2).

In earthquakes, magnitudes of seismic shaking cannot be mitigated, but only the related response of an exposed asset. The measures to increase resistance of bridges to seismic shaking are discussed in Section 4.2.2 and the case study in Section 4.3.2.

Unplanned traffic restrictions due to poor condition of bridge elements are very rare in countries that have already established preventive maintenance practice. Nevertheless, some deterioration processes can be hidden and/or undetected, such as reinforcement/pre-stressing steel corrosion. The advanced corrosion occurs due to extensive chloride ingress. The causes for this may be leaks in drainage within box girders, leakage of water through expansion joints or any other case of constant wetting of concrete surfaces for several years. A solution would be shortening of the inspection interval on e.g., expansion joints to reduce the duration of this process and thus lowering the extent of deterioration. Still, for some structures there is no viable inspection solution since the related elements/surfaces are hardly accessible (e.g., the back of retaining walls or foundations).

Additionally, corrosion damage of reinforcement may vary considerably and even inspections that include local removal of concrete cover may leave significant uncertainties. When there are observable damage or displacements, it may be that deterioration is well advanced thus it is late for prevention measures (i.e., a failure had already occurred). So, the only viable solution for engineers is to be resourceful by measuring/monitoring various parameters at micro-locations that can serve for a reliable and timely identification of severe degradation processes. With respect to concrete structures, various monitoring solutions have already been developed (e.g., [35], [36]), which rely on multi-sensors to gather parameters, for example: pH, free chloride concentration, concrete electrical resistivity, steel potential temperature. The measurement results from sensors are validated in a proprietary software and interpreted to generate adequate notifications and suggest a maintenance strategy.

3.3 Case Studies

3.3.1. Wildfires in Portugal

Forest fires are a widespread hazard that can deeply alter the landscape where they develop and spread, endangering infrastructure, property and human lives. Among countries in the world that suffer systematically from forest fires (e.g., during dry seasons), Portugal stands out not only by the number of occurrences but also by the size of the burned area (Figure 3.6).

In 2017, Portugal was by a large margin the country most affected by forest fires, accounting for 41% of the entire burned area mapped within Europe for that year. On this occasion, after a winter and spring with low levels of precipitation and a severe summer in terms of weather-related circumstances favourable for spread of fires, there were 21,006 forest fires identified, leading to 539,921 ha of burned forest and agricultural area. The severity of these fires in some cases was high due to significant amount of fuel materials present in forests, leading to the two tragic episodes that resulted in a high number of casualties.

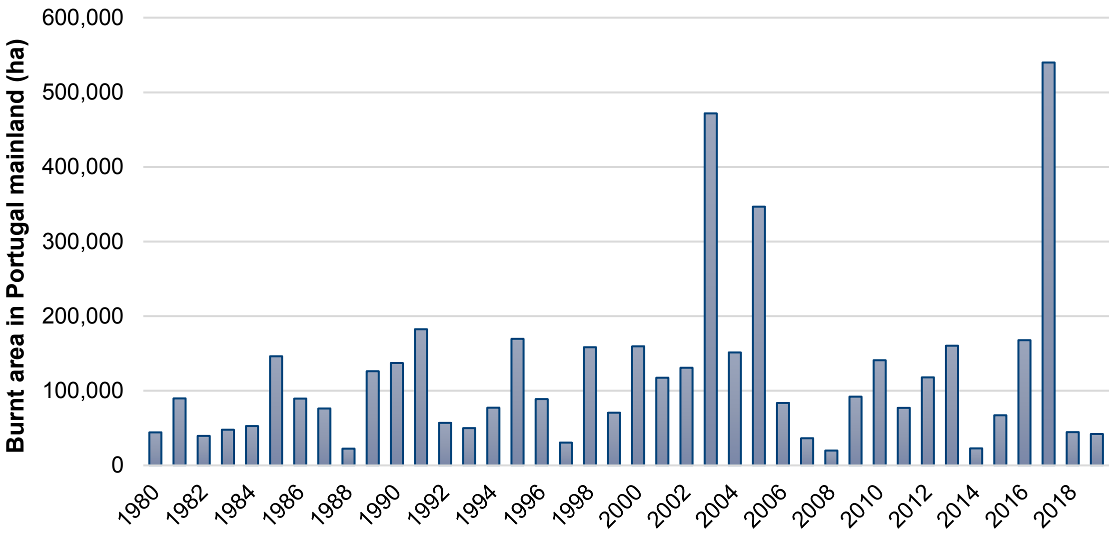


Figure 3.6 Burnt area in Portugal mainland from 1980 to 2019, [37].

Chronologically, the first episode took place in the municipality of Pedrogão Grande (in the centre region of Portugal) where a huge fire started on June 17th, affecting also the neighbouring municipalities. It resulted in 66 deaths (65 civilians and one firefighter) and significant losses in buildings and forest area. Most of the deaths (47) occurred on the road i.e., inside or nearby vehicles, as people were trying to escape from the affected villages (Figure 3.7).

a) b)

Figure 3.7 Wildfire in Portugal on June 17th, 2017. a) burnt area scars in central and northern Portugal, [38]; b) burnt vehicles on the road near Pedrogão Grande, [39].

A second episode occurred on October 15th, after the typical fire season but with a context of a very dry summer, when over 500 ignitions in the same day across the country resulted in 46 deaths and once more in considerable losses in burned buildings, industrial and agricultural areas (the burnt area was more than 200,000 ha). The dire consequences of these tragic events triggered a wide discussion within Portuguese society, leading to several changes in the applicable law and regulations related to wildfire prevention and management. In the aftermath of these events, the changes in road infrastructure management were implemented.

Regarding road infrastructure management, the key issue was to assure how the process of dealing with roadside vegetation would meet the following objectives:

- To reduce the risk of fires spreading from roadside ignitions,
- The use of roads as discontinuities to limit or interrupt the spread of fires, and
- Guarantee safe access for emergency vehicles or an escape route

In terms of regulations, before 2017, there were already general rules for vegetation control on the roadside: a stretch of 3.0 m width for mowing from the end of the shoulder, and then a stretch of a 7.0 m width for selective tree cutting or pruning, totalling 10.0 m wide managed stretch at the roadside (Figure 3.8).

Figure 3.8 Road cross-section and distances for mowing and selective cutting or pruning in Portugal, [40].

For National Roads under the jurisdiction of Infraestruturas de Portugal SA, this vegetation management was part of the multi-annual routine maintenance contracts. Here, the fixed work quantities were annually managed to achieve the best possible results given the available resources, focusing at first on assuring the required visibility distance for drivers. However, the fire-related risk assessment was a responsibility of the municipalities and there was no common and well-established framework developed to support the optimised allocation of resources and work programming. Additionally, in many cases the 10.0 m strip at the roadside required for the vegetation management was under a private property, and there were not flexible legal processes that could expedite actions in such cases.

In late 2017, implementation of a new legal framework for fire management started i.e., the SGIFR - Integrated Wildland Fire Management System. The current version of the law is from the 2021 [41]. Considering the complexity of the programmes for prevention and operational stage needed to set up the system, and since quick results were expected in the wake of the terrible fires which occurred in that year, three main priorities were identified:

- The need to protect people,
- Managing fuels around buildings and critical infrastructures, and
- Reduction of the number of ignitions

With respect to the management of road infrastructure, at the beginning of 2018 the criteria applicable to fuel management in the roadside strip (10.0 m) were clarified, including: the distance between tree canopies, maximum vegetation heights, and distance from buildings or infrastructures (Figure 3.9).

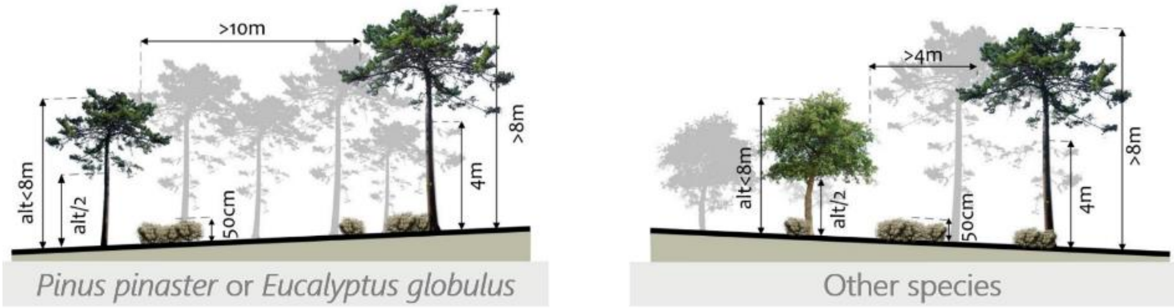


Figure 3.9 Rules for fuel management related to trees and vegetation in Portugal, adapted from [42].

Infraestruturas de Portugal SA, implemented and operated the design changes on this topic, considering its role as road infrastructure manager of more than 14,000 km of the Portuguese National Road Network. To comply with the legal framework that structures the new fire management system, Infraestruturas de Portugal SA, started to annually perform the following activities:

- Participation in the preparation of the municipal plans for the Defence of Forestry Against Fire (PMDFCI) and appointment of a representative in the Municipal Forest Defence Committees, for the articulation of activities to be developed annually,
- Compilation of the approved municipal plans and its combination with roadside vegetation management area under its responsibility in the company’s GIS,
- Identification of roadside areas to be intervened in each year of the plans' validity,
- Programming of the works to be carried out within the scope of maintenance contracts, and
- Execution of the works by the end of June 2018, before the start of the critical period and considering the restrictions due to adverse weather conditions

As key changes in the process, at first, it should be noted that the municipal plans are made based on parishes (the smallest administrative unit in Portugal), following a comparable framework and having a risk assessment process that results in different levels of priority (Figure 3.10a), to be managed annually.

Secondly, GIS processing capabilities are extensively used to obtain detailed roadside areas to be annually managed, supporting the several stages, from the maintenance contracts design and valuation to the prioritisation of the work itself (Figure 3.10b). Further, by using GIS, the cases when the 10.0 m strip subject to vegetation management is under a private property, are additionally identified, allowing the development of contracts specifically meant to support the works when the owner is not able to act (Figure 3.11).

The length of the roadside vegetation management was related to about 6,400 km (45% of the network). The initiatives as well as the public awareness following the 2017 events, have certainly contributed to the reduction in the number of fires and burnt area in the following years, increasing the safety and resilience of road infrastructure in Portugal.

a) b)

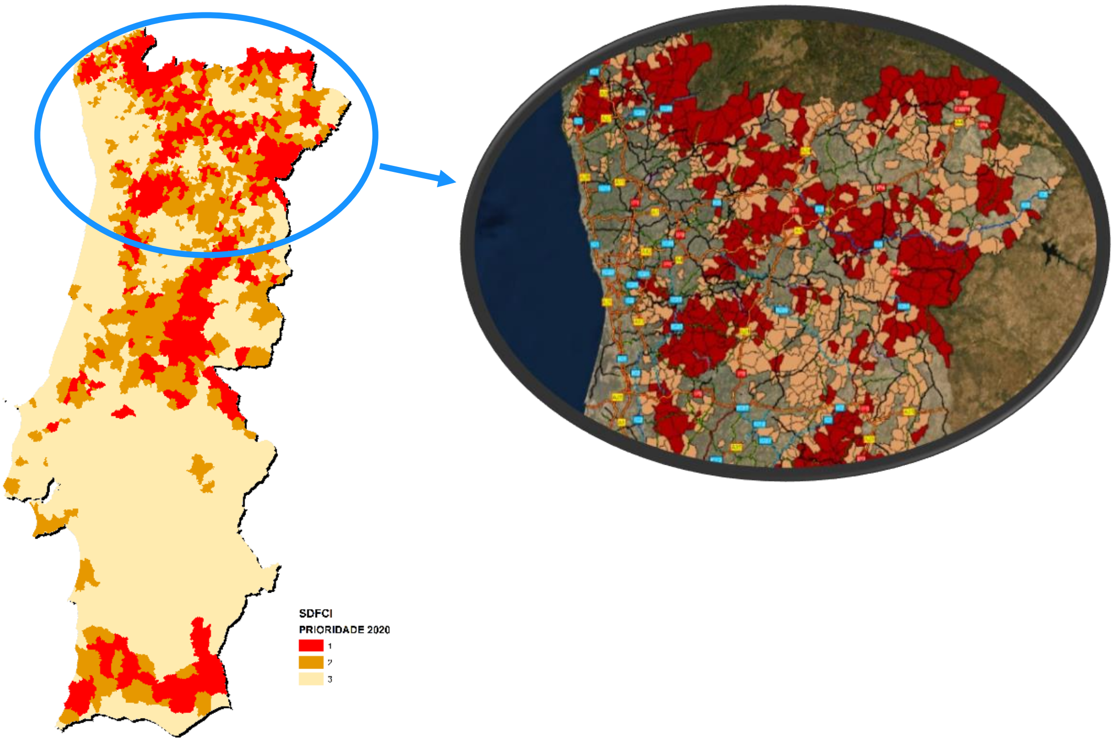


Figure 3.10 The priority levels according to fire management system in Portugal. a) priority levels, PMDFCI, 2020; b) GIS processing to calculate the detailed areas to be managed; ©IP.

Figure 3.11 An example of a GIS processing for the identification of the roadside vegetation management areas under private property in Portugal, ©IP.

3.3.2. Flood hazard in New Zealand

Flooding is New Zealand's most frequent natural hazard (the light blue colour in Figure 3.12) and responsible for the highest number of declared civil defence emergencies. With over a hundred cities and towns located on flood plains, New Zealand has a long history of living with floods. Development, population growth and land use changes are putting greater pressure on catchment areas while the impacts of flooding are leading to increased social, economic and environmental disruptions. On average, a major freshwater flood (150-year return period) occurs every eight months across the country.

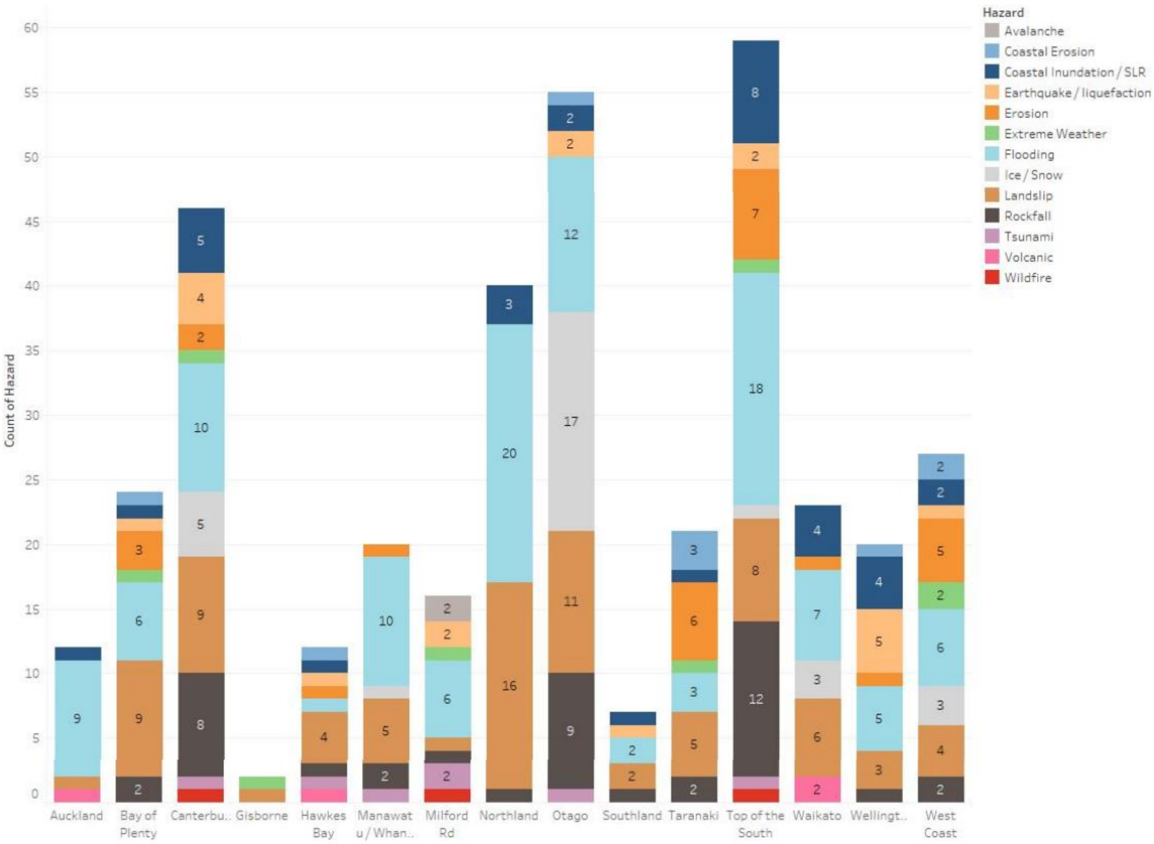


Figure 3.12 Summary of Natural Event Occurrences by Region and Type in New Zealand, [43].

Levels of physical protection vary across the country, depending on past decisions, community expectations and the risk profile of each area. Flood risk has been managed in a number of ways, including physical protection, as well as land use, building controls and warning systems. There are no standardised national data sets, indicators or methodologies to assess risk across the country. In general, physical protection standards (e.g., [44]) have shown:

- Urban areas are usually protected from at least 1 in 50-year floods from large rivers,
- Smaller urban and rural areas protection vary from a 1 in 50- to 1 in 100-year standard for residential areas, to a 1 in 20- up to a 1 in 50-year level for rural land, and
- Stormwater systems generally aim to prevent flooding in a 1 in 10-year event but can be greater

Without accurate measurements it is difficult to say whether these levels are suitable now or in the future. The fact that there have been few fatalities suggests that on the whole the levels have been sufficient in the past in terms of protecting individuals, but property losses and damage costs have been increasing as a result of large-scale events, and some fatalities have occurred, [45].

The New Zealand Central Government contributes to the cost of response and recovery after a flood, including all costs of repairing state highways. However, prudent investment in the threat reduction phase would help local governments to more effectively manage flood risks and prepare for climate change. Thus, the Waka Kotahi New Zealand Transport Agency (in further text Waka Kotahi) has developed a range of tools, frameworks and materials to help plan for increasing resilience of the New Zealand transport system. One of the tools developed to implement resilience solutions is through the State Highway Improvements activity class "Low-Cost Low Risk", resilience fund (see Section 7.2.2.2). The Waka Kotahi has undertaken a number of low-cost low-risk solutions in relation to flooding. One example is the case of floodwaters from the Otiria Stream that backs up to State Highway 1 (SH1) and inundates the carriageway as well as the low-lying community of Moerewa during a flood event (Figure 3.13). The highway is rendered impassable and in events of such magnitude it is sometimes necessary to evacuate people or relocate properties to higher ground.

The flood affected SH1 is a popular tourist route, and the surrounding areas benefit from the tourism. In addition, Moerewa has a freezing works and cattle sales yard within the township, and it is also a link forestry route. The AADT on this and affected roads is ca. 9000 vehicles [46], and during a road closure there is an alternative route for highway traffic, which adds an additional 52 km to the journey during moderate flood events.

a)

b)

Figure 3.13 Flooding at Otiria Stream, Moerewa, New Zealand; a) aerial view of the site; b) a moderate flood event overtops a bridge; ©NZTA.

Historical records indicate that the bridge at the stream (Figure 3.13) has a two-year recurrence overtopping interval. The flooding occurs after sustained rainfall and the area has been known to stay flooded for up to one-two days in major events. Maintenance remedial works have been required to repair and protect the pavement following flood events. The longer-term solution is to address the flooding inundation by replacing the Otiria Stream bridge at an estimated cost of NZ$ 5.0 million, as well as raising the approaches to the bridge and the Moerewa township. The low-cost low risk solution is to provide benching works adjacent to the Otiria Stream, which provides a reasonable catchment for the flood waters during periods of heavy rain, the cost of this work is estimated at NZ$ 725,000. While the flood backwaters cannot be avoided, the benching works will provide a catchment for the back waters and will reduce the frequency of flooding events that induce an overtopping. This will ensure that the highway is still trafficable during a 10-year return period flood event, compared to the current two-year return period.

3.3.3. Landslides & rockfall hazards in New Zealand

New Zealand has a high number of landslides & rockfalls as it sits on the boundary of two tectonic plates and also experiences frequent rain with some events being very significant (>100mm of rain in 24h). Much of the land is a hill country, formed by rivers cutting into soft clay rocks. Many slopes are unstable, with weak layers of volcanic ash and roads have been cut into hillsides often contributing to slope instability. Some landslides and rockfalls move whole mountain sides, i.e. millions of cubic metres of material, such as in the Kaikōura earthquake (Section 0), while others are of lesser extent and can be cleared in hours (Figure 3.14).

a) b)

Figure 3.14 Examples of rockfalls impacting the State Highways in New Zealand; a) a rockfall at SH30 Ongaroto; b) a rockfall at SH2 Waioeka Gorge; ©NZTA.

Each year Waka Kotahi, other roading authorities in NZ, landowners and railway operators spend millions of dollars clearing landslips, which seems like a never-ending task. Recently, there have been several incidents with dire consequences. In May 2018, SH1 was closed, and traffic issues emerged after another rockfall struck between Clarence and Mangamaunu regions [47]. In August 2019, a large rockfall triggered by heavy rain closed SH6 between Haast and Makaora. In November 2019 a road user was killed by a falling rock while driving their car, [48].

There are several solutions to mitigate a threat of rockfall, but there is always a residual risk that needs to be accepted. Funding is a known constraint for all road authorities but the ability to implement low-cost solutions swiftly improves network reliability, user safety and therefore resilience, while undertaking more detailed investigations, assessing performance of prior solutions and prioritising higher investment needs. The Rock Hazard Rating system (Section 7.2.2.3) in combination with the "Low-cost Low-risk" resilience funding (Section 7.2.2.2) have been and continue to be effective tools for the Waka Kotahi to implement solutions that mitigate a threat of rockfall hazard. Having a clear process, which is applied consistently across a national network, ensures that highest priority sites are identified each year and have the best opportunity to be funded. The fact that these sites require repairs and ongoing maintenance e.g., to remove spill material from behind the rockfall fence are a testament to the measure effectiveness.

One of permanent, low-cost solution that can be installed reasonably quickly are rockfall fences. Once installed, they require regular inspections and maintenance, including component replacement and clean-out of debris from behind the fence which can be an issue in the difficult-to-access locations (Figure 3.15a). Suspended mesh and cable nets are also used where the mesh or net is used to intercept rocks, absorb the energy and direct dislodged rocks into a catchment area (Figure 3.15b). These types of solutions are useful in areas with frequent rockfalls and can be installed in difficult-to-access locations. They do require ongoing maintenance and asset owner's manuals should be developed specifying frequency of inspection and component replacement.

a) b)


Figure 3.15 Examples of a rockfall protection in New Zealand; a) a road fence; b) the suspended mesh and cable nets in and around Kaikōura; ©NZTA.

Installation of temporary rigid barriers are often used as an initial response to rockfall events. These are generally prefabricated concrete barriers linked together, temporary waterfilled plastic barriers or even shipping containers (Figure 3.16a). Many of these temporary barriers become permanent as funding is often a constraint. These however pose a safety risk as generally they do not meet the current crash test standards. These types of temporary barriers require regular maintenance or are often overtopped by larger slip events (Figure 3.14). Permanent, earthen embankments can be constructed in a range of shapes and sizes with varied internal reinforcing elements and facing materials (Figure 3.16b). These types of barriers have greater energy absorbing capabilities than suspended mesh, cable nets or fences.

a) b)


Figure 3.16 Rigid barriers for rockfall protection in New Zealand. a) shipping containers used as temporary barriers at SH1 Kaikōura South Coast; b) permanent earthen embankments protecting both rail and road infrastructure; ©NZTA.

4. MITIGATION OF ROAD ASSET FAILURES DUE TO THREATS

4.1 Overview

For many threats it is not viable or even possible to reduce asset exposure, so it is worth considering to increase resistance of assets to sustain extreme threat magnitudes. The primary aim of these measures is decreasing the probability of an asset failure in a threat scenario, which corresponds to increasing robustness aspect of resilience. Such measures may comprise adapting, retrofitting or strengthening of assets to enable adequate load/displacement capacity in circumstances that could emanate from a threat. Here included can be various enhancements and add-ons to an asset, (e.g., electro-mechanical equipment). Further, if an asset has several possible failure modes due to a threat magnitude, a desired failure mode may be controlled with a measure e.g., preventing an uplift of a bridge superstructure in a flooding event but accepting that fact that washing away of access roads at abutments may occur.

In this Chapter, the measures for increasing resistance of pavements and bridges to the failures from the most common threats are presented. Further, in the scope of two case studies are mitigation measure of a specific bridge failure mode due to frequent flooding in Mozambique and seismic retrofitting of bridges in New Zealand.

4.2 Increasing resistance of road infrastructure

4.2.1. Pavements

To complement the mitigation measures discussed in the previous chapter (Table 3.1), measures that increase pavement resistance to withstand extreme conditions are here considered (Table 4.1). In particular, extreme heat can induce various damage both in case of concrete and asphalt pavements. As the surface of the concrete heats during the day, the top of the slab tends to expand faster than the bottom resulting in upward daytime curling (Figure 4.1a).

a) b)

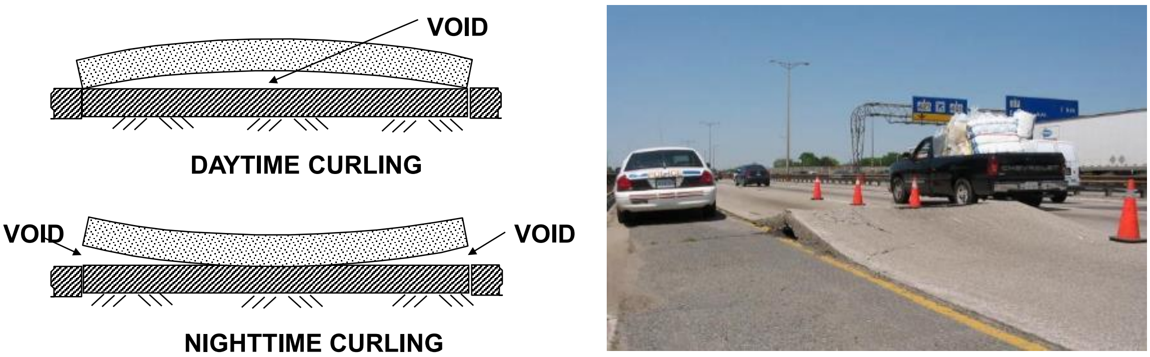


Figure 4.1. Damage to concrete pavement due to extreme heat. a) curling process of concrete slabs; b) "blow-up" damage at concrete slabs; ©Hein, D.

Loading of the concrete in this situation will result in higher stresses in the middle of the slab and possible transverse cracking. During the colder night-time temperatures, the surface shrinks faster than the bottom resulting in the end of the slabs curling upwards. This may result in slab spalling and cracking at joints. The expansion of the concrete slabs due to high temperatures results in pressure at the slab joints, causing a "blow-up" damage which pose a significant threat to vehicles

(Figure 4.1b). Sustained high temperatures can cause asphalt pavement to soften, resulting in rutting and shoving damage. High heat may be accompanied by drought conditions, causing asphalt pavement to crack and make it more sensitive to water ingress. Besides the standard adjustments in the asphalt mix, recently there had been promising application of polymer asphalt binders (HiMA) that can increase pavement life even with reduced pavement thickness, [49].

On some occasions, threats do not cause any physical damage to pavements, but generate unsafe driving conditions leading to accidents, e.g., reduction of skid resistance in a case of excess water on pavement due to high intensity rainfalls. Such cases are also considered as a failure mode of infrastructure (Section 2.2).

Table 4.1 Increasing resistance of pavements to failure modes.

Threat	Potential damage/failure state	Increasing of pavement resistance
Increase in average/ maximum air temperature & Heatwaves	Pavement surface rutting, flushing and bleeding (due to reduction in asphalt binder stiffness)	Adjustments to asphalt mix design - more angular shaped aggregates and higher stiffness asphalt cement; Use of HiMA (high polymer binders); Adjustments to concrete mix design - aggregates with lower coefficients of thermal expansion, higher temperature curing, reduced water content;
	Spalling and blow-us of concrete slabs (curling and warping effect due to thermal expansion)	Cooling fluids through pipes within or beneath the concrete pavement; Installation of additional expansion joints;
	High deformation under stress (due to lower asphalt concrete dynamic modulus)	Use of solar reflective coatings to reduce the absorption of infrared radiation and thermal conductivity of asphalt; Using light coloured aggregates, colour pigments;
Higher frequency/ magnitude of rainfall; Flooding	Joint faulting in concrete pavements (erosion caused by pumping of a trapped water under a concrete pavement)	Active program of joint repair/replacement program to prevent water ingress to the pavement.
	Excess water on pavement surface (as the main cause of accidents)	Improvement of the surface friction of concrete pavements (skid resistance) by "diamond grinding" or "shot blasting"; Improvement of the micro and macrotexture of the pavements by adapting aggregate types and gradations.
Decrease in frequency of very cold days	„Fatigue cracking“ due to increased stress on the surfaces that would typically stay frozen longer due to insulating effect of snow (Figure 3.4c)	Crack and joint sealing and the repair of other defects, to reduce moisture ingress.

4.2.2. Bridges

Protective and sacrificial structures cannot aid bridges in some threat circumstances, thus the measures that increase resistance to expected failure modes may be considered.

For example, in case of earthquakes, one approach is to increase load/displacement capacity of structure or its elements by providing either additional structural support, reinforcements, or enhancements (see Section 4.3.2). Some bridges may benefit from strengthening e.g., jacketing and external post-tensioning (Figure 4.2a), which increases the capacity of structural elements such as beams, piers, and the joints that connect them. However, some bridges are more likely to survive a seismic event provided rigid elements are replaced by more flexible or even sliding elements, which allow for free movement e.g., of entire span without cracking, breaking, or elements hitting each other. In some cases, linkage elements are added to prevent excessive deformation (Figure 4.7b). Deformed elements can be replaced after a seismic activity is over to return structural integrity. There are also approaches which imply triggering of a desired failure mechanism. Here included are perhaps controversial measures where certain sections/elements of a structure are weakened to break in a threat scenario, leaving the rest of the structure intact. Repairing of the damaged sections/elements is deemed more acceptable than rebuilding of the whole structure.

a) b)

Figure 4.2 Examples of increasing resistance to failure modes. a) external post-tensioning; b) a viscous damper on the Meiko West Bridge, Japan, [50]; c) weakening of a bridge steel section to contain crack growth (a drill stop method), [51].

Resistance to failure modes in an earthquake can be indirectly increased by application of damping or isolation systems, which once installed are regarded as an integral part of a structure. Seismic dampers work as shock absorbers and transform motion energy into heat, which helps dissipate the seismic shaking energy (e.g., Figure 4.2b). The dampers are meant to prevent excessive displacement of elements and rigid structural components from hitting into each other. In the case of base isolators, material is removed from the foundation and replaced by isolating pads. These structural elements separate the exposed structure from the ground, altering the response of the structure to the occurred shaking magnitude.

Another type of approaches is to control a failure mode as in the “drill stop” or “crack arrest hole” method, which has been used to contain the (fatigue) cracking of steel sections (Figure 4.2c), that do not weaken the structure. But it was proven ineffective in mitigating the crack growth and considered as a temporary measure implying frequent inspections and monitoring. Recently, an enhanced method “StopCrackEX” is adapted from hole cold expansion and expanded bushing technology proven in aerospace industry, [51]. This method prevents the re-initiation of a crack at the opposite side of the drilled hole. It is being successfully applied on bridges in the U.S., where it demonstrated significant maintenance, preservation and repair cost savings and extended structural inspection cycle.

With respect to flooding events, there are preventative measures on bridge foundations to mitigate failures resulting from local scour (i.e., soil erosion at substructures). These measures are usually applied when a bridge is assessed as a scour critical, even after some scouring has already occurred on site. In the scope of these measures are foundation strengthening (e.g., reinforcing/extending) and modifications of pier/abutment geometry. The measures on foundations are applied to prevent a bridge failure when a river channel bed is lowered to an expected elevation by scour, or to restore structural integrity after some scour has occurred and left the structure vulnerable to future threats (Figure 4.3a). The measures that involve geometry modifications of piers (e.g., debris deflectors, gabion stones) are applied to mitigate future, expected local scour at bridge substructures (Figure 4.3b).

a) b)

Figure 4.3 Increasing resistance of substructures to scour. a) a pier strengthening following river scour; b) debris deflector at the pier that also reduces local scour potential; ©NZTA.

4.3 Case Studies

4.3.1. Bridge strengthening in the face of a flooding in Mozambique

The National Administration of Roads in Mozambique (ANE) is in the process of introducing adaptation measures for the improvement of the resilience of road networks, affected by cyclic floods due to cyclones. When tropical cyclones occur during the wet season in Mozambique, heavy rainfall and extended flooding may occur, leading to severe consequences to road infrastructure and its stakeholders. The main objective is to reduce the risk of road network failure (inaccessibility, collapses, damage, etc.) in future flooding events. This is done by adopting improvements in the design of new roads and bridges according to [52], but also considering technical adaptation measures that can help to mitigate failure of existing bridges.

A project was initiated to focus on bridge superstructures that may sustain flood-induced damage and related measures that can be implemented during construction, rehabilitation and maintenance of bridges. In the scope of the project are the design considerations and construction of simple supported girder bridges, accounting for the previous experiences with bridge failures. During a flood, a bridge superstructure may undergo a buoyancy uplift and lateral water forces, resulting in washing away (Figure 4.4a). This type of water impact and the related failure mode have been rarely considered in the past design and construction of bridges in Mozambique. A simple and inexpensive adaptation measure has been considered, to introduce cast-in-place concrete column elements extended from pier to deck soffit (Figure 4.4b), to resist lateral water forces during flood events.

a) b)

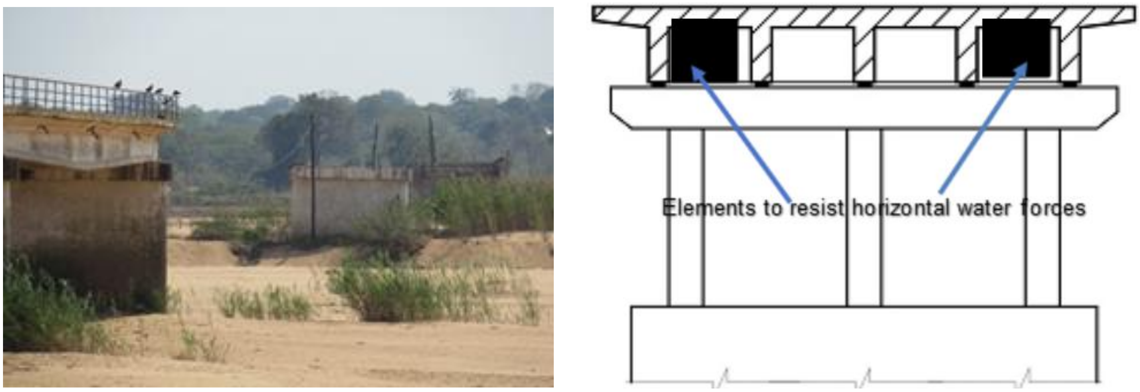


Figure 4.4 Strengthening of bridges to flooding in Mozambique. a) a bridge where its superstructure is lifted and washed away; b) adaptation measure for a bridge deck to resist water forces during a flood; ©ANE.

So far, this and similar adaptation measures are recommended to be included in decision-making, aiming to primarily increase the robustness of bridges in the face of oncoming flooding events in Mozambique. Although these measures have not yet been introduced in bridge design and construction specifications, it is mandatory that all rehabilitation and construction of bridges have measures to avoid the washout due to floods. These measures need to be checked and approved by ANE.

4.3.2. Seismic retrofitting of New Zealand bridges

All of New Zealand is susceptible to a seismic hazard, but the anticipated intensity varies across the country. The Institute of Geological and Nuclear Science (GNS) has developed a seismic hazard map (Figure 4.5), showing peak accelerations for a given period. Since November 2010, New Zealand has experienced multiple seismic events with Richter magnitudes Mw >= 6.0 (peak ground acceleration >= 0.05g).

Waka Kotahi manages about 4300 bridges and significant culverts (those with the total waterway area greater than 3.4m^2) on the state highway network, of which 65% were built before 1970. The related bridge stock has an estimated replacement cost of NZ$ 11.0 billion. As seen in Figure 4.6, the cast in-situ concrete bridges were common before the mid-1950’s and the use of precast concrete superstructures started to become popular after the mid-1950’s.

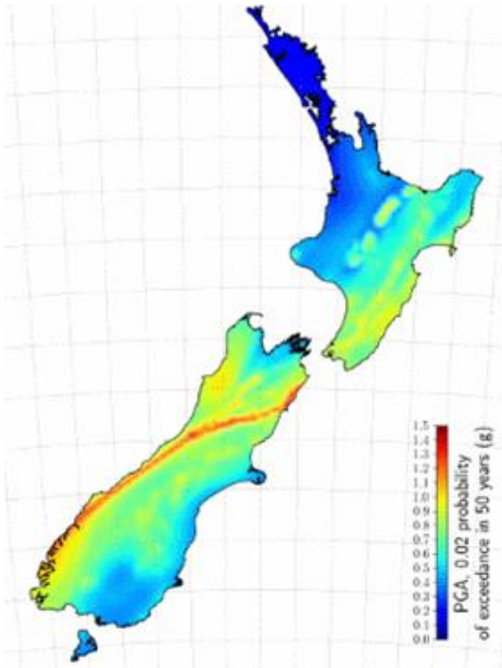


Figure 4.5 GNS seismic hazard map, which shows the 2% probability of exceedance of peak ground acceleration from earthquake shaking in any 50-year time window; [15].

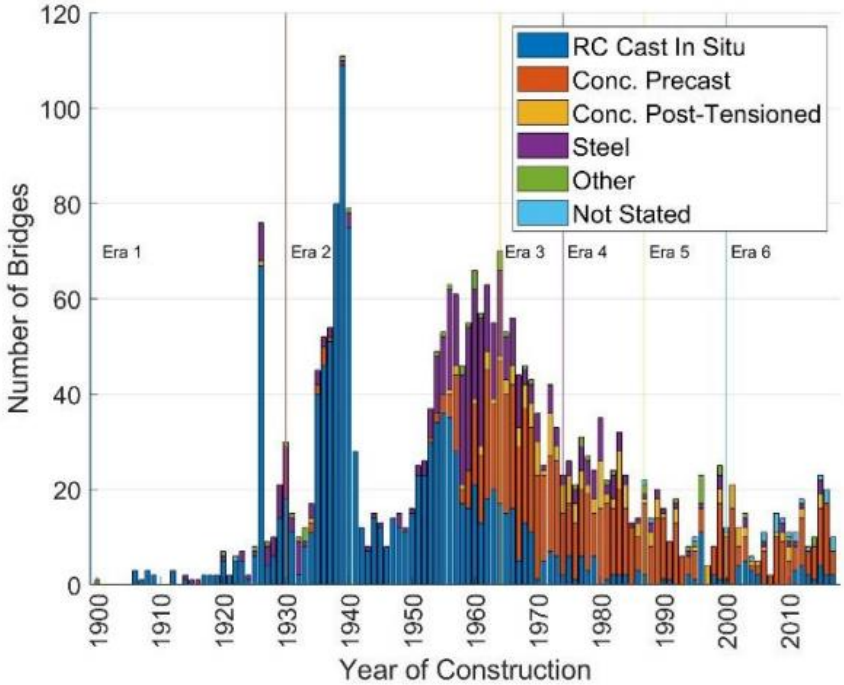


Figure 4.6 Distribution of the year of construction and superstructure types for State Highway bridges built after 1900 in New Zealand, [53].

In 1998, Waka Kotahi initiated screening of the earthquake resistance of bridges to identify those structures that may not perform satisfactorily during seismic events. The screening of the bridge stock was undertaken in stages, like a sieving process with increased degrees of fineness, to minimise the number of structures requiring a detailed analysis. The primary output from the initial screening procedure was a list of bridges, ranked in order to consider an appropriate, detailed seismic assessment. The initial screening process comprised the following stages:

- Stage 1 – Identify the bridges to be excluded from screening,

- Stages 2 and 4 – Gather relevant asset information from databases and documentation,
- Stage 3 – Preliminary screening (identify bridges for partial exclusion from the screening),
- Stage 5 – Seismic Attribute Grade (SAG) is calculated using 3 inputs:
  - Hazard index (seismicity and geological factors),
  - Importance index (AADT, route strategic importance, utilities on the bridge), and
  - Vulnerability index (based on the bridge's age, length and structural capacity)
- Stage 6 – Site Inspection is undertaken to resolve queries and identify issues
- Stage 7 – A specialist's review
- Stage 8 – Finalizing the SAG values to account for engineering judgement from the Stage 7.
- Stage 9 – Risk Assessment - identification and description of seismic risk, assessment of likelihood and consequences and determine options and cost,
- Stage 10 – Economic ranking indicator (ERI), and
- Stage 11 – Ranking for further analysis.

The procedure adopted for final ranking was based on four criteria, considered in order:

- The priority assigned to the route on which the bridge is located,
- Whether the bridge was likely to collapse onto facilities putting lives at risk,
- The Economic ranking Indicator (ERI) of the risk event of the highest ERI, and
- The number and significance of the risk events associated with a bridge.

Seismic screening and the subsequent ranking of bridges was completed in 2003:

- 3813 bridges and significant culvert structures were inspected,
- 1491 were eliminated early in the process (stages 2 through to 4),
- 1351 were further eliminated in the screening process as they were designed after 1972 or their seismic performance was assessed as good,
- 971 bridges remained and the SAG for each bridge was calculated (Stages 5 through to 8),
- 381 bridges were identified with high and significant risk levels (Stage 9). 192 were on the priority I routes, 72 on the priority II routes and 71 on the priority III routes., and
- 188 bridges from the total number of bridges were identified to have linkage deficiencies (i.e., lack of positive horizontal linkage between span and support or specific provision for large relative displacements).

The most common issues identified in the screening process were related to:

- a lack of information relating to foundation soils,
- seismic screening criteria did not consider some factors, such as aging, deterioration, and loss of material strength, that are important for a reliable structural performance evaluation. However, State highway bridges are generally well maintained - in a few cases it was assessed that the effect of this type of degradation was minimal, and
- many of the New Zealand rivers are braided and are also prone to sudden large changes in the volume and significant scour around foundations (e.g., Figure 4.3a).

Most of the seismically screened bridges were designed pre-1975, after which modern seismic design codes were introduced in New Zealand. It is a fact that the bygone seismic lateral loads in the design were much lower in comparison to the design requirements in 2014/2018 standards [54], and the applied linkage detailing that should enable a ductile behaviour was inadequate. If the 2014 standard was adopted for a seismic assessment of the existing bridge stock (typically more than 40 years old), the assessment criteria would lead to uneconomical retrofits. To counter this, a different set of guidelines were developed for a seismic assessment, where an earthquake with a different return period is used in evaluation:

- Bridges with a remaining life >= 50 years: a 1,000-year earthquake return period, and
- Bridges with a remaining life < 50 years: a 500-year earthquake return period.

Here, the remaining life is related to the timing when bridge needs to be replaced due to the poor condition and expensive maintenance, justified via a benefit-cost-ratio (BCR) analysis.

The detailed seismic assessment focused on the top 50 bridges from the initial screening process, with the intent to assess their seismic response and recommend an adequate retrofit solution, if necessary. By April of 2004, 47 bridges had had a detailed seismic assessment completed. A peer review was then undertaken to cover structural, economic and consistency aspects of the assessments, to estimate the extent of retrofitting and to recommend alternative retrofit solutions. The reviewers found that the detailed assessments were carried out to a high standard with all the vulnerabilities identified and most of the viable retrofits considered. The peer review did find that:

- The use of BCR analysis as part of the detailed assessment process was not very helpful and was subsequently removed from future detailed assessments,
- ERI while broadly correct for indicating the highest priority bridges, was of little help for ranking the larger group of bridges of intermediate risk, and
- Future detailed seismic assessments need to include more technical details (e.g., minimum requirements for span linkages, spacing of reinforcement to prevent buckling in plastic hinge zones, damping from structure-soil interaction, use of settlement slabs at abutments, fixing for elastomeric bearings, etc.)

Common techniques used in the seismic retrofitting (e.g., Figure 4.7) of New Zealand bridge stock included:

- Fibre wrapping of tops and bottoms of pier columns,
- Strengthening of beam-column joints at piers,
- Steel jacket pier columns,
- Rock anchors at abutments,
- Replace or strengthen all bearings and strengthen some linkages,
- Connecting a deck to transoms,
- Strengthening of abutments with new piles,
- Improvement of abutment slopes,
- Instalment of shear keys for transverse loading at both abutments,
- Instalment of new diaphragms at abutments and piers, and

- In-span hinges.

a) b)

Figure 4.7. Examples of earthquake retrofit solutions on State Highway bridges in and around Christchurch, New Zealand. a) a shear key detail; b) a linkage bar detail; ©NZTA.

There were several issues identified during the retrofit design, which have further refined the retrofitting process and solutions, including:

- Inadequate ductility and/or shear capacity of bridge elements,
- Inadequate capacity of beam-column joints,
- Inadequate capacity of hold down bolts and/or linkage systems,
- Unseating. In some cases, the demand on the existing hold-down bolts and linkages and their supporting element was just too big, so the retrofit was not practical,
- Dealing with more than one deficiency. In some cases, a global solution (e.g., replacement) was considered as potentially cheaper than the retrofit of numerous separate deficiencies, and,
- Liquefaction. In most instances it was accepted that the risk is there and that spending, large amounts of money would be difficult to economically justify.

As a result of the 2010, 2011 and 2016 earthquakes, Waka Kotahi was able to assess the performance of its bridges that had been exposed to these seismic events.

4.3.2.1 Darfield Earthquake in 2010

The average magnitudes in the Darfield earthquake ranged from a 140 to 580-year return period, so many newly constructed state highway bridges did not exceed their design levels. However, the bridges built prior to 1971 were subjected to shaking intensities greater than applied in their design. Waka Kotahi commissioned a report [55], investigating the performance of bridges following this earthquake. Inspected were 24 bridges of which most were designed before 1971. Only 7/24 bridges experienced significant structural damage. There was a significant settlement of the approaches at 9/24 bridges accompanied with a significant liquefaction at 5 of these. However, only two bridges were seriously damaged by lateral spreading resulting from liquefied soil layers or failure of weak soil layers.

Seven of 24 inspected bridges had been previously retrofitted with linkage systems. The performance of the linkage bars on these bridges remains unknown, as the period of shaking and related displacements were relatively small. Note, two of the bridges that were not retrofitted with linkages, sustained severe damage of abutment diaphragms. Overall, the bridges performed better than expected in this earthquake and it seemed certain that the retrofitted bridges benefited from the installation of linkage bars and shear keys. One learning was that design of bridge elements must take account of relative member strengths and that linkage bolts should preferably be designed to form a limiting yield force.

4.3.2.2. Christchurch Earthquake in 2011

The shaking intensity of 1300 to 1500 years' return period occurred during the Christchurch event. The earthquake induced liquefaction and associated ground damage, and the lateral spreading was the principal cause of damage to bridges in this earthquake event. Liquefaction generally caused extensive damage to abutments of bridges, but also to the piers closest to the abutments, due to the imposed loads on the pier foundations resulting from the lateral spreading. Several bridge abutments were damaged from lateral spreading where the ground was prone to liquification (Figure 4.8).

a) b)

Figure 4.8 Damage to a bridge structure in Canterbury resulting from liquification in Christchurch earthquake. a) fissures and settlements on the bridge approach; b) an abutment rotation; ©NZTA.

Thirteen of 25 state highway bridges inspected had received significant structural damage. Two of the 13 bridges suffered serious damage from liquefaction lateral spreading. Repairs required on the significantly damaged bridges included:

- Repair of diaphragms and linkage bolts, relatively straightforward but costly,
- Repairs to abutment walls (Figure 4.9a) and some of the piers, and
- Major repairs to abutments to restore joint gaps.

While minor repairs included:

- Spalling and cracking damage at the bases of pier columns,
- Abutment linkage bolts, abutment deck joints and paved abutment slopes,
- Improvements to soil embankments.

Key findings from the sample assessment of bridges highlighted:

- Current design standards are adequate,
- The importance of quality detailing and construction, and good ongoing maintenance,

- The consideration of liquefaction and lateral spreading as an integral part of bridge design need to be reinforced in design standards

a)

b)

Figure 4.9 Various damage to a bridge in Canterbury in the Christchurch earthquake.
a) cracking of a bridge abutment; b) settlement of an abutment; ©NZTA.

4.3.2.3. Kaikōura Earthquake in 2016

The shaking intensity corresponding to a 1000-year return period occurred during this event (7.8 magnitude on the Richter scale). Soil ruptures occurred on multiple fault lines in a complex shaking sequence that lasted for about two minutes. It was followed by a 2.50 m tsunami. For more data on the consequences in this event, see Section 5.3.1. Bridges generally performed well, although some experienced damage and partial access was able to be restored in most instances with weight and lane restrictions. In addition, some bridges were totally closed as the access was compromised by settlement of the approaches (see Section 6.2).

One experience from this earthquake is discussed on the example of a Clarence River bridge, which is approx. 40 km north of Kaikōura on SH1 (Figure 4.10a). The bridge was constructed in 1968, and ranked as one of the top 50 for seismic assessment (see Section 4.3.2). According to the detailed seismic assessment and Bridge Manual standards, all vulnerable elements required strengthening (full retrofit). Alternatively, partial retrofit at a lower cost comprising midspan hinge strengthening only could be applied to reduce the risk of a crippling damage. However, the retrofit options had poor economics. A preliminary design was completed for the retrofit concept, but was found to be impractical due to: the large number of cables/bars required to provide the longitudinal linkage, the size of the anchorage system required to anchor the linkages, and very confined access and working space.

A new retrofit concept was developed to maintain horizontal and vertical shear transfer, but not moment transfer, across the hinge joints. The estimated rough order of cost was NZ$ 350,000 and was implemented in 2008. Post-earthquake damage to the structure was observed. The bridge suffered shear damage (diagonal cracks) at one of pile caps (Figure 4.10b) but in general the superstructure performed well. The bridge was considered serviceable and was opened to traffic with a 30 km/h speed restriction. The later repairs cost NZ$ 3.0 million with a further NZ$ 3.0 million spent on strengthening other piers. On the same river but 11 km upstream, Glen Alton Bridge collapsed (Figure 4.10c, d), where estimated cost to replacement were from NZ$ 24.0 million to NZ$ 47.0 million. This bridge was not previously retrofitted.

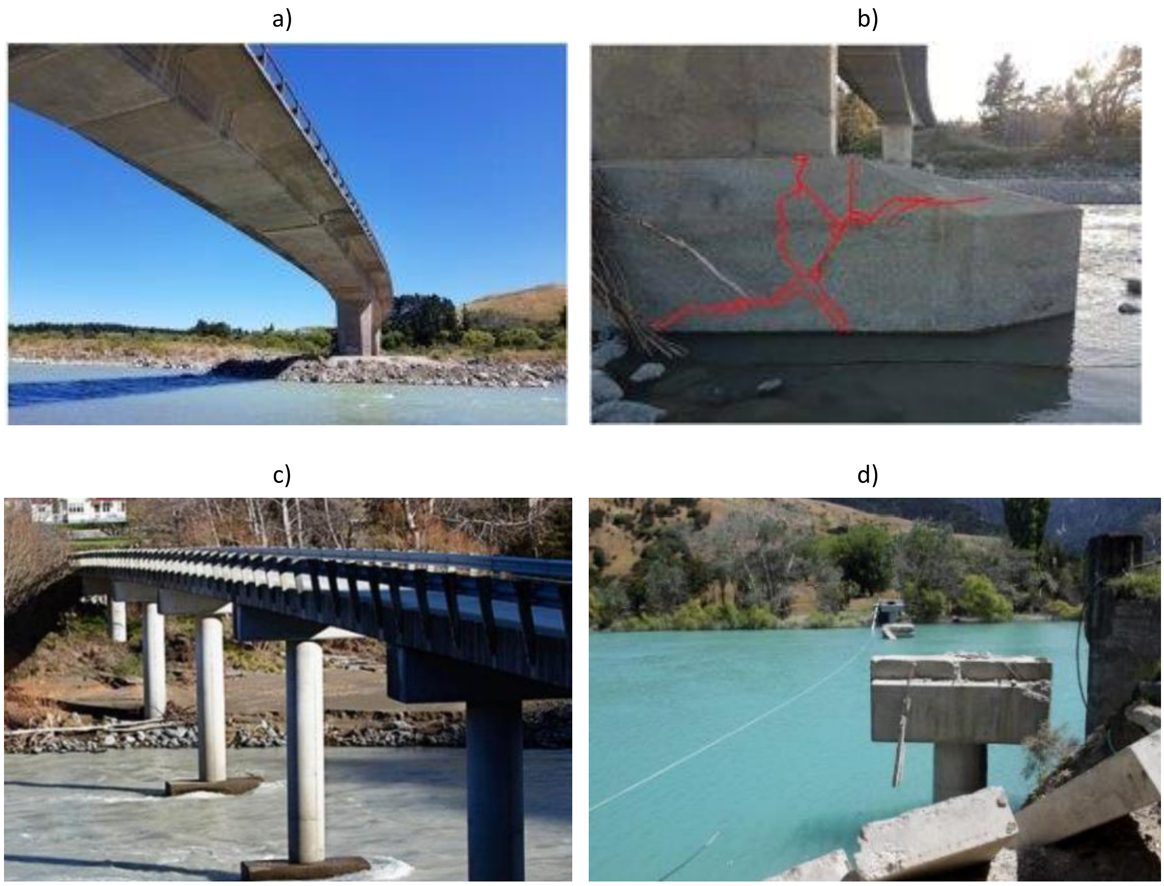


Figure 4.10 Performance of two bridges in the Kaikōura earthquake in 2016;
a) Clarence River Bridge before the earthquake; b) damage to the pier pile cap at Clarence River bridge; c) Glen Alton bridge before the earthquake; d) the collapse of Glen Alton bridge; ©NZTA and Kaikoura District Council.

4.3.2.4. Lessons learned on bridge seismic retrofitting

The Darfield, Canterbury and Kaikōura earthquakes provided a valuable opportunity to learn from the performance of bridges in real events. It is evident from the field inspections that state highway bridges in New Zealand have been well maintained and that has had a positive effect on how the bridges have performed during the seismic events. The lessons learned included:

- The bridges built before 1972, which were well detailed for dead and live loading and reasonably well maintained, generally performed well,
- The bridges which had exposure to marine environments, and which had already significant spalling and corrosion damage on reinforcement, generally experienced extensive damage, and,
- There was significant settlement of the backfill behind the abutment walls. Had settlement or approach slabs been fitted, this would have reduced the impact of settlement. However, spending large amounts of money in the future for such retrofit would be difficult to economically justify.

Also, an adequate structural detailing is the key to bridge good performance in earthquakes:

- Older bridges that were tied together, effectively performed as locked-in structures with very good results. Some even performed better than newer bridges with less appropriate detailing, and
- Seismic retrofit using linkages to tie bridge spans together and prevent them from dropping off was a low-cost and a highly effective treatment.

Lessons learned have and continue to lead to improvements to seismic assessments and retrofitting practices. In example of New Zealand, it would be worthwhile including a section in the Bridge Manual on earthquake assessment, highlighting the need to avoid conservatism and recommending the use of simplified analysis procedures based on displacement-based design methods. In general, the detailed assessment analyses can be very time consuming and costly and may not provide any more reliable prediction of performance than simplified methods. Lower cost but less accurate assessments may be sufficient for decision making. It was also concluded that future mitigation measures can be improved by considering information on soil properties on-site and current bridge condition.

While bridges are considered as critical elements of the transport system, the performance of other assets in route integrity need to be considered as well – e.g., in the Kaikōura seismic event, land instability was the governing issue. Therefore, the benefit of retrofitting a bridge need to consider the wider vulnerabilities of the transport system, especially for low redundancy of network (see Section 5.3.1).

5. MITIGATION OF THE CONSEQUENCES OF ROAD ASSET FAILURES DUE TO THREATS

5.1 OVERVIEW

There are threat scenarios where either reducing asset exposure (Chapter 3) or increasing resistance of assets to threat magnitudes (Chapter 4) are not viable options. It may also happen that despite timely preventative measures a threat occurs and causes asset failure(s). In many cases, electro-mechanical equipment is the weakest link and its failure by rule implies traffic (operational) restrictions until necessary repairs are performed. Instead of focusing on protection and resistance of assets, an option would be to conduct measures aimed at mitigation of short and long-term consequences of eventual failures. One such option is improving redundancy aspect of network resilience e.g., by building/upgrading a detour, providing back-up systems for electro-mechanical equipment or increasing traffic mode interchangeability (e.g., road to rail). However, increasing redundancy in the face of eventual failures is not always a feasible measure, especially for the cases where a threat scenario impacts multiple infrastructures.

For some threats, impacts of asset failures on stakeholders can be roughly anticipated and the initial response to failures may be planned well in advance, with a goal to limit the extent of consequences. Increasing of preparedness to such asset failures by performing proactive measures is related to improvement of resourcefulness aspect of resilience and fosters recovery, indirectly improving of rapidity of response. The proactive measures comprise e.g., stationing of aggregate stockpiles, rockfall/debris removal equipment and stocking up of components for temporary structures, to be within reach of rescue and repair teams. The proactive measures need to be planned and executed timely, prior the occurrence of a threat and failure event i.e., relate to medium to long-term planning., in difference to recovery measures in Chapter 6.

In this chapter, the importance of flawless functioning and redundancy of electro-mechanical equipment is emphasized, in the cases of tunnels and retaining walls in Austria. The case studies presented from Switzerland and New Zealand demonstrate the importance of improving/maintaining redundancy and related resourcefulness.

5.2 PROACTIVE MEASURES

5.2.1. Electro-mechanical equipment in tunnels

Flawless functioning of electro-mechanical equipment is essential for operation of tunnels. If this equipment fails for any reason, there may be a range of operational restrictions triggered (e.g., from speed reduction to a full closure). For the approximately 320 tunnel tubes of the Austrian highway system, traffic restrictions due to failures of electro-mechanical equipment are rather frequent i.e., have to be applied several times a week, which is regulated in [56]. The restrictions cause consequences to traffic users in the road network and the duration of such restrictions usually do not exceed several hours. Besides regular maintenance, the mitigation measure in the face of these consequences can be achieved by providing redundancy of equipment. Exhaust fans, surveillance cameras, illumination and guidance systems are usually installed in such a way that a failure of individual parts can be easily overcome. Additionally, there is in most cases an emergency power supply available for a case of a power outage.

Besides enabling the normal operation, electro-mechanical equipment may be installed on site to mitigate consequences of a specific threat/failure scenario. This is a case with supressing a fire in a tunnel. The most common causes of a fire come from: vehicles that are already on fire when entering a tunnel, collisions, overheated vehicle equipment (e.g., bearings, brakes, tyres, engines) or overheating/malfunction of electro-mechanical equipment (e.g., fans). Although there are ventilation systems and escape shafts usually envisioned in design for such scenarios, each tunnel can be regarded as highly confined and insulated space, allowing rapid-fire growth and limiting working duration of firefighters. Due to a fire, tunnel functionality and user safety is endangered, and the related consequences depend on fire localization, load and duration. Since the occurrence of a fire threat in a tunnel, originating from an external source, cannot be viably mitigated, the efforts are directed to timely mitigation of its load and duration, which govern the extent consequences. The relevant electro-mechanical equipment comprises:

- Fire detection systems ahead of a tunnel portal, which are commonly temperature triggered (e.g., Figure 5.1),
- Fire extinguishing system, and
- Ventilation system controlled according to a fire location.

a) b)

Figure 5.1 Thermo-scanner facilities to detect overheated heavy vehicles, Karawankentunnel, Austria; a) a truck entering the tunnel; b) thermal cameras installed at the tunnel's entrance; ©ASFINAG.

5.2.2. Anchored retaining walls

Anchored retaining walls are redundant systems and a failure of a single anchor does not usually cause further damage(s). However, prestressed anchors can fail in a brittle fracture. This may happen due to corrosion or stress corrosion cracking, which cannot be reliably and timely discovered in inspections. When fracturing, the strain energy in the anchor is converted into kinetic energy. The loosened part of an anchor moves slightly out of the wall and anchor heads may be catapulted onto a roadway, potentially endangering the road users. In order to avoid/mitigate the consequences of this failure scenario, the anchor heads need to be secured (Figure 5.2).

a) b)

Figure 5.2 Mitigation of consequences of an anchor failure in Austria; a) an anchor failure; b) an anchor head protection; ©ASFINAG.

5.2.3. Accidents and other human-made threats

An accident event near or at a construction site on a road link can have a larger impact on the functionality of a road network than the same event would have under normal operation of a road link. This is because the redundancy of a network is already impeded by the construction site. For instance, if a car breaks down next to a construction site, this may cause a total closure of an affected road link, which generates consequences to stakeholders. A mitigation measure in the face of such events is to timely provide a crane on the construction site, which gives the possibility to clear the roadway in a short period of time i.e., improves the rapidity of response aspect of resilience.

The damaged/deficient road safety equipment can pose as an indirect threat to road users. This is the case when an impact attenuator is damaged and/or when a restraint system is broken at a median road strip as a consequence of a vehicle crash. In such cases the traffic must be restricted (e.g., speed limitation, a lane closure) until the damage are repaired. The duration of traffic restrictions can be minimized by a fast repair, which is usually possible within 24h, provided that there are timely allocated resources, which are close and available.

5.3 CASE STUDIES

5.3.1. Experiences from the Kaikōura earthquake in New Zealand

During the Kaikōura earthquake in 2016 (Section 0) the Kaikōura township was severely damaged, and its rail, State Highway 1 road (SH1) and sea transport links were cut off (Figure 5.3a). Landslides and embankment failures caused the most damage and disruption to the transportation infrastructure (Figure 5.3b, c, and d). While the road traffic had to be completely rerouted inland via the Lewis Pass, the rail line going along the Kaikōura coast was completely cut-off (150km track, 20 tunnels & 10 bridges were severely damaged). Pre-quake AADT on detour roads was approx. 1,200 veh./day with 200 heavy commercial vehicles per day. With the closure of the rail line (1.12 Mil. tonnes of freight annually), post-quake traffic volumes rose immediately to approximately 1,995 veh./day with 600 heavy commercial vehicles per day. The unaffected road network (i.e., detours) had a redundant capacity to account for the additional traffic from the exposed road and rail line, but for the road network users there were other (long-term) consequences, which included:

- Increased travel distance, travel time and related fuel use (an additional 110 km and additional 2.5 h),
- Increased travel distance affected the travel time predictability and reliability, which is of particular importance for freight, and
- Increased potential for delays and road accidents, due to the winding and mountainous nature of the detour

Since there was a concern about the ability of the detour routes to sustain the increased traffic volumes over time, there were post-event pavement renewal/strengthening treatments required as the detour roads had a lower classification compared to that of SH1. In the light of the occurred event, these measures and upgrades can be understood as increasing network redundancy in the face of a similar, future events.

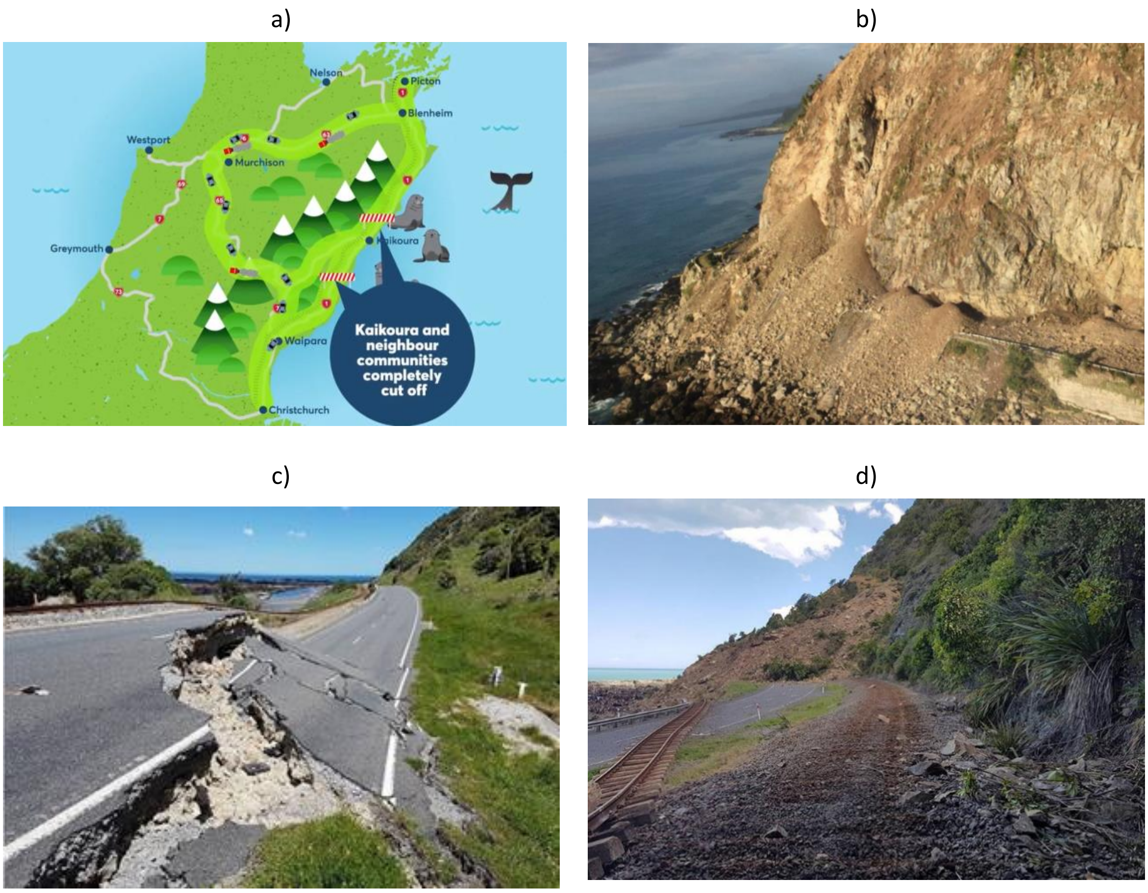


Figure 5.3 Reduced functionality of transportation network due to Kaikōura earthquake; a) affected transportation network with redundancy; b) a significant rockfall closing SH1; c) an uplift affecting both road and rail line d); ©NZTA.

5.3.2. The new Gotthard Tunnel tube in Switzerland

The Gotthard Massif has a long history of connecting Northern and Southern Switzerland. Although not used during Roman times the road over Gotthard was intensively used in the Middle Ages. The first tunnel was a railway tunnel that was built in 1882, which at the time was an engineering marvel.

It is 15 km long and still in use today. In context of this report is of interest the first road tunnel that was opened in 1980. It is a two lane tunnel with a length of 17 km. At the time this was the longest road tunnel in the world.

The collision of two trucks on October 24 2001, ignited a fire in the tunnel with temperature over 1200°C, which led to 11 deaths and many injured [57]. Although the tunnel was reopened in December 2001 for traffic, there were significant concerns regarding the tunnel safety. It is therefore that more efficient ventilation was implemented, the drip feed system was imposed that ensured that not too many trucks are in the tunnel, thermal scanners at the portal were introduced to identify overheated vehicles, lighting was improved, communication system enhanced, etc. However, the greatest improvement in safety is to come from the construction of the second tunnel tube. Furthermore, the existing tunnel is in need of a comprehensive renovation, which is not possible under traffic. To ensure that this important road link can remain open during the renovation, the Federal Roads Office FEDRO (ASTRA) is building a second tunnel tube (Figure 5.4). The Swiss Government has approved the construction of the second road tunnel parallel to exiting one in 2014 and the construction started in 2020. The costs of this project are estimated at approx. CHF 2.14 billion [58].

The new Gotthard tunnel is 16.9 km long and is estimated to be opened for traffic in 2029. At the same time the existing tunnel will be closed, and renovation work will start. The renovation is expected to be completed in 2032. Once both tunnels are opened for traffic, it will be guided through the tunnels on a single lane and without two-way traffic. This means that the capacity of the tunnel will not be increased, which is in compliance Swiss constitution – adopted in referendum in 1994 - that forbids a further growth of the traffic capacity across the Alps.

Although the primary motivation for the second Gotthard tunnel was safety improvement, it also significantly improved resilience of the route by offering redundancy through Gotthard Massif. Given that in case of closure of one tunnel, which can occur due to a threat, an accident or a maintenance measure, the other one can offer the full capacity, which is a prime case of improved resilience. This effectively means that in case of closure there is no resilience loss. Clearly, to a certain level there is redundancy also today since there is also a Gotthard Pass Road, but it is closed in winter.

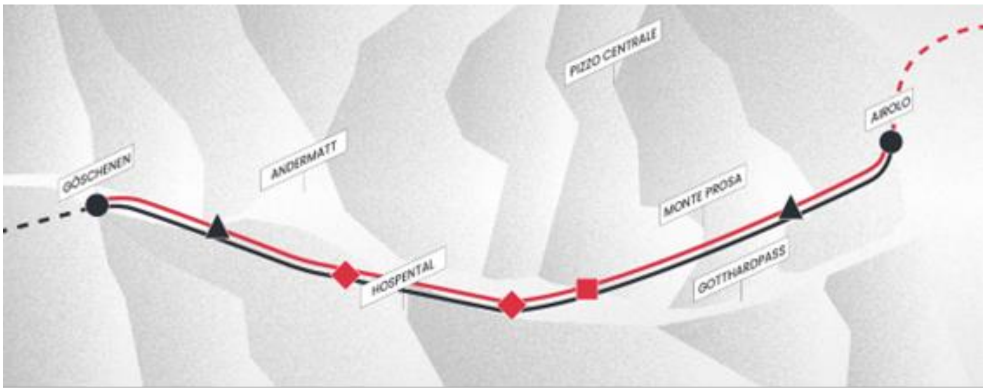


Figure 5.4 Increasing route redundancy by building the new Gotthard Tunnel tube (in red), Switzerland, ©ASTRA.

5.3.3. The failure of Bristenstrasse road in Switzerland

The “Bristenstrasse” in Canton Uri, Switzerland is the only road connection to the village of Bristen, which was severed on March 5, 2017 by a land slide (Figure 5.5a). It is still unclear what was the cause of the land slide, but perhaps the high weather and temperature fluctuations in the few days preceding the failure could be the reason. The owner and operator of this road reacted fast and the road connection to Bristen was re-established on May 12, 2017. Initially Bristen was only accessible on foot, but from March 15 the almost 100 years old funicular railroad (Figure 5.5b) was reopened after safety test were performed, [59]. Originally, this funicular railroad was built for Amsteg powerplant in 1920. The existence of the old funicular increased the redundancy and enabled the population to overcome the temporary cut off from the rest of the world. This simple case shows that the functionality of transportation infrastructure can be maintained in a cross-modal manner.

a) b)

Figure 5.5 Mitigation of consequences of a road failure; a) Landslide at the Bristenstrasse, ©Canton of Uri; b) the old funicular railroad re-opened to transport passengers, ©Amsteg SBB power plant.

6. RECOVERY

6.1 OVERVIEW

Following an occurrence of a threat and resulting asset failure(s), comes the recovery phase. The main goal in this phase is to efficiently return the affected infrastructure in the pre-failure state or at least to the state, in which the demand can be met, with optimal allocation of human, financial and material resources at disposal. This process needs to be fostered by meticulous activity planning e.g., prioritizing among, access of emergency response groups, repair/rebuild of damaged assets and supply of vital services. The main pre-requisite for a successful recovery is an adequate level of preparedness, which is achieved by: prudent allocation of machinery/equipment, continuous training and improvements of response teams and backed up with a swift legal response that allows utilization of emergency budgeting. The recovery measures relate to the rapidity of response aspect of resilience and associated resourcefulness. Besides repair/rebuild activities, these measures also imply early warning measures and execution of temporary solutions that ensure minimum redundancy of the damaged infrastructure. The main difference to measures explained in previous chapters is that the recovery measures solely relate to the short-term planning, i.e., time just before failures are about to occur and the post-failure period.

The measures in this chapter are focused on decreasing duration and extent of consequences of occurred failures and fostering recovery process. The presented case studies exemplify flooding aftermaths (Canada, Switzerland, Serbia, Argentina and China) and best practices in dealing with initial response and recovery (Canada, New Zealand, Switzerland).

6.2 IMPROVING RESOURCEFULNESS AND RAPIDITY OF RESPONSE

During a threat impact on infrastructure and when the threat magnitudes decrease, an adequate initial response is essential to ensure access for emergency teams, evacuation, supply of vital services and commencement of repairs. The initial response as well as the whole recovery process needs to be supported by prudent resource planning, which is governed by a level of preparedness to failures (see Chapter 5). Here, the main resource categories for an efficient recovery are listed:

- Human resources (incl. competences and expertise):
    - Emergency (e.g., firefighters, medical staff, police, volunteers),
    - Assessment and repair (e.g., engineers, workers, volunteers), and
    - Management & planning (e.g., engineers, decision-makers)
- Materials and machinery
    - Stocked components in maintenance facilities, for replacement of damaged parts and/or building temporary structures,
    - Machinery/equipment available and in range, and
    - 24/7 readiness of maintenance facilities
- Financial resources
    - 24/7 maintenance service contracts for various equipment/machinery, and
    - Emergency budgeting

The decisive and swift response will prevent exacerbation of consequences and mitigate eventual cascading failures of other infrastructure. For example, clogging of drainage facilities due to a rainfall may cause road closures due to excessive water on the road. Usually, unclogging can be quickly performed (in a few of hours), provided response teams are nearby with adequate equipment/machinery (e.g., sewage trucks).

Rapid response in debris removal is of the upmost importance, especially when the affected part of the network has low or no redundancy. One such example is the Sea to Sky Highway in Canada, which given the mountainous conditions and steep slopes, is constantly being challenged to remain in service. During high rains in 2006, a rockslide left a massive piece of rock that had to be drilled and blasted on the roadway to affect its removal (Figure 6.1a). In 2008 a large rockslide occurred consisting of nearly 16,000 m^3 of granite and covered the highway and adjacent rail line (Figure 6.1b). While there were no injuries caused in this rockslide event, the only highway connecting Vancouver with the Cities of Squamish and Whistler were closed for 5 days to allow for rock blasting and rock clearing via excavators and heavy haul vehicles, and safety evaluations prior to their reopening.

a)

b)

Figure 6.1 Rockslides on the Sea to Sky Highway, British Columbia, Canada; a) a rock slide caused by high rain conditions in 2006; b) Porteau Cove rock slide in 2008, British Columbia, Canada; ©BCMoTI.

In a case of large-scale events where infrastructure is damaged at multiple locations, the recovery can last for many years. During this period, it is necessary to ensure both sufficient and steady level of all resource categories. The full recovery and upgrade works following the Kaikōura earthquake (Section 5.3.1) were a national effort for New Zealand, lasting from November 2016 - June 2021. North Canterbury Transport Infrastructure Recovery (NCTIR) alliance was formed with the objective to restore the road and rail networks following and make them safer and more resilient. With 1700 workers from New Zealand and overseas in Kaikōura at the peak of the project, in June 2017 the 300-bed NCTIR village was opened to house some of the team with support from local organisations and local businesses throughout the project (Figure 6.2).

Figure 6.2 NCTIR village for workers on the recovery from the Kaikōura earthquake, New Zealand, [60].

6.2.1. Temporary solutions

The complexity and applicability of temporary solutions may vary on the type of assets and extent of failures. The main idea is to provide at least the minimum operation functionality (see Figure 2.3) of the affected network while repairs are underway. A few short examples are given here, while the case study in Section 6.3.3 elaborates more on the topic of temporary bridges.

Following the Kaikōura earthquake in 2016 (Section 5.3.1), the most of affected road bridges were able to be opened quickly but with restrictions. The most common damage was settlement at bridge abutments, which was considerable at a couple of locations (Figure 6.3a), and these had to be bypassed with alternative roads or roads where temporary bridges were installed. In some cases, damage was minor and mitigated with fill or asphaltic concrete to form small ramps as a temporary solution (Figure 6.3b). The related pavement repairs on the approaches restricted bridges to a single lane with a 30 km/h speed limit for up to five days following the earthquake.

a) b)

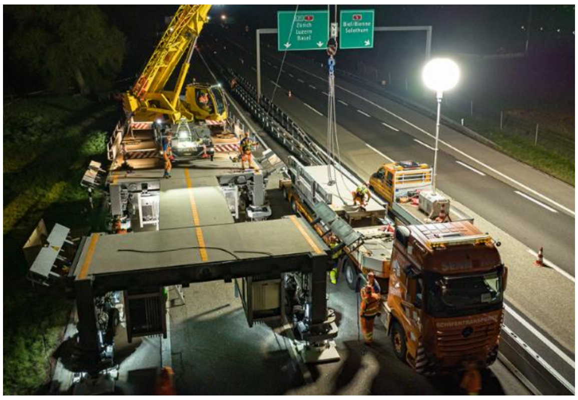
Figure 6.3 Settlements at bridge abutments in Kaikōura earthquake, New Zealand; a) a severe settlement (>0.5m) at a bridge near Oaro; b) a minor settlement mitigated with a temporary ramp (fill); [61].

In order to mitigate consequences of closures on a highway during execution of pavement repairs, a traffic bypass via a bridging structure may be considered (e.g., Figure 6.4). This allows the works to be executed without significant traffic disturbance, and from a resilience aspect this solution can be considered as a temporary increase of redundancy. The innovative solution "Astra Bridge" has been recently applied on a pilot project in Switzerland in 2022, [62]. During the project the following was confirmed:

- The auxiliary bridge works both conceptually and technically. The roadworks under the bridge can be carried out as planned both in terms of schedule and quality,
- The automatic repositioning of the bridge was a success and traffic could drive over the bridge without incident, and
- Roadworks could be carried out during the day – less construction noise at night and more socially acceptable working hours, with safely separated working zone from the traffic.

Despite the benefits, application of the ASTRA Bridge also brings some challenges. These include assembling and dismantling the bridge on the carriageway and the space required to store the bridge parts. In addition, the bridge can only be used on certain motorway sections. Currently, the ASTRA Bridge is being optimised as it became apparent that the gradient of the entrance and exit ramps for heavy goods vehicles was not satisfactory, requiring the ramp rounding, i.e., the change in gradient, to be improved in order to enhance comfort and speed when driving. The adapted solution is scheduled to be applied in 2024.

a)



b)

Figure 6.4 Mobile auxiliary bridge, A1, Switzerland; a) the construction phase; b) in operation; @ASTRA.

In spite of regular bridge inspection and maintenance, the effects of overloading, high frequency of traffic and uneven road surface can lead to sudden damage at expansion joints (e.g., deformation or loss of a finger joint). These damages pose as an acute danger to road users (Figure 6.5a), thus immediate remedial actions are necessary. To mitigate severe traffic restrictions, the damaged joints can be secured with cover plates, a so-called "mini flyover system", until repairs are carried out (Figure 6.5b). The common repair techniques imply blocking of the lamina, welding with the neighbouring lamina of an expansion joint (Figure 6.5c) or the replacement of the entire joint.

a)

b)

c)

Figure 6.5 Response to a failure of an expansion joint on a bridge; a) a damaged joint; b) "mini flyover system" - anchored in asphalt (a short-term solution), c) a plate welded to the damaged joint (a long-term solution); ©ASFINAG.

6.3 Case Studies

6.3.1. Recovery of highway infrastructure from an atmospheric river event in Canada

The Category III atmospheric river event occurred between November 14th and 16th, 2021 (Figure 6.6), led to floods and landslides that killed five people and a cut-off of all road and rail routes between the city of Vancouver and the rest of Canada. The unprecedented, catastrophic damage to highways occurred, resulting in many communities being affected, people being displaced from their homes, and major supply chain disruption. It was the costliest natural disaster in the history of the British Columbia (BC) province, with CA$ 675 million of insured damage, [63].

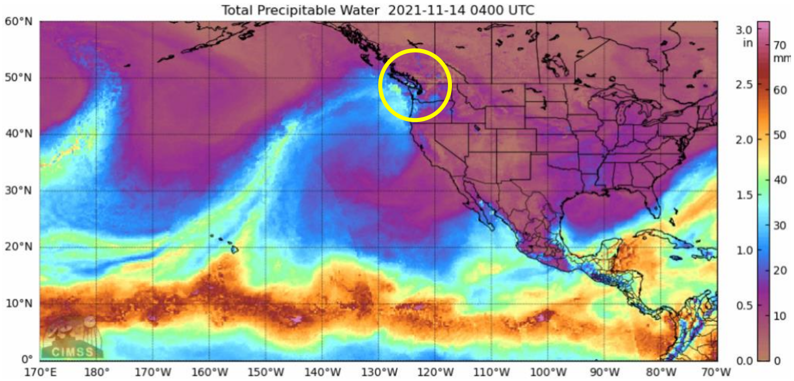


Figure 6.6 Atmospheric river event affecting British Columbia province (in the yellow circle), Canada, [64].

During the rainfall, several basins experienced a 100-year water levels and 16/32 stream gauges in the affected areas recorded peak flows greater than ever recorded. An already very wet November had compounded to the problem. The storm was unique in how far inland it penetrated. The wind speed and direction drove the precipitation up and over the Coquihalla summit into areas that typically experience half the precipitation of southern catchments. East facing drainages were particularly impacted, on the windward side of the North Cascade Mountain ranges. These drainages often experience orographic rain and are therefore unaccustomed to heavy precipitation. The event impact hit large areas of wildfire from summer 2021, which resulted in a much higher runoff of water due to the reduced vegetation cover.

The City of Hope is the junction of Highways 1, 3, 5 and 7 (Figure 6.7). These corridors were simultaneously closed, isolating Hope from the rest of the country, and the Lower Mainland from the interior. At the same time, Highway 99 was also closed due to a tragic landslide. The event came in from the southwest and passed over Vancouver Island and into the Lower Mainland (the southwest corner of the province), which is the economic hub of BC with the highest population.

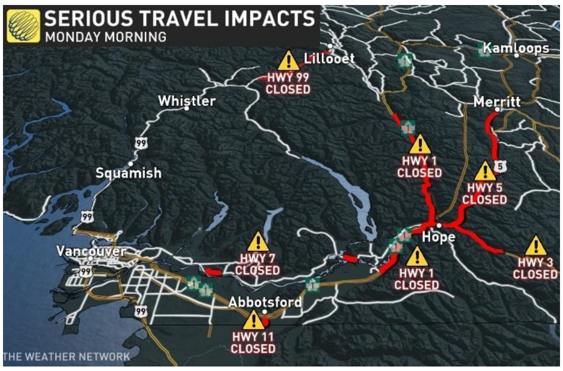


Figure 6.7 A brief overview of the BC province and the impacted corridors, Canada; ©BCMoTI.

Over 60 sites were affected between November 14th-17th. Highway 1 was flooded between November 15th and November 21st and it remained closed, available only for emergency traffic, while damage to infrastructure kept the highway closed further east. Washing away on Highway 8 occurred at 25 locations with a 1.0 km washout of both lanes at one location (Figure 6.8a). Damage to the highways north of Hope city were mainly due to high-volume, fast-moving creeks and rivers. The water caused erosion and debris torrents leading to a culvert failure and several complete bridge failures. The three spans the Bottletop Bridge on Highway 5 collapsed, and a section of the road was washed away (Figure 6.8b). The Tank Hill underpass and the CP Rail line were heavily impacted. The CP rail line was wiped out, a bridge was severely undermined, culverts were completely plugged and both lanes of the highway were completely washed away (Figure 6.8c).

a)

b)

c)

Figure 6.8 Damage to infrastructure due to the atmospheric river event ; a) a major washout on Highway 8; b) the collapse of Bottletop Bridge on Highway 5; c) destroyed rail and road lines at the Tank Hill underpass; ©BCMoTI.

The main goal of the affected communities was to restore the functionality of critical infrastructure, focusing on reopening the highways. The immediate response started on the November 15th. At several locations, during the event, there was no provincial highway open. Tremendous efforts included repair of a dike breach by the city of Abbotsford along with protection of the critical Barrowtown pump station. The BC Ministry undertook damming activities along the Sumas Canal to retain flood waters inside the channel, preventing additional flooding (Figure 6.9a). Slide damage was cleaned up east of Chilliwack. This all led to Highway 1 re-opening to public traffic on December 2nd, 18 days after first closing. To preserve safety of road users, travel restrictions were enforced at affected locations (e.g., Figure 6.9b). Highway 99 re-opened shortly after the event but restricted to essential travel only and vehicles < 14,000 kg. All other routes were restricted to essential traffic only. The Coquihalla re-opened to commercial vehicles only 36 days after the event. It included the Coquihalla Pass system that permitted workers to gain access to the highway.

a)

b)

Figure 6.9 Initial response to the atmospheric river event in Canada. a) protection along the Sumas Canal; b) traffic restrictions; ©BCMoTI.

The work on the Tank Hill underpass began within 12 hours of the event occurrence and the temporary re-connection of Highway 1 was completed 65 days after the event occurred (Figure 6.10a). The construction of new bridges commenced in a month following the event at some sites (Figure 6.10b and c), while in some cases the temporary bridges have been installed (Figure 6.10d). The efforts on the restoration of the Jessica bridge (Figure 6.10b) included:

- Over 200 pieces of equipment and over 300 people working around the clock, and
- Moving over 400,000 m^3 of fill and blasting over 130,000 m^3 of rock (enough to fill over 50 Olympic-size swimming pools)

The work on the restoration of the damaged infrastructure in BC was completed in 2022.

a)

b)

c)

d)

Figure 6.10 Quick restoration activities. a) Tank Hill underpass (January 14, 2022); b) Jessica bridge on Highway 5 (December.13 2021); c) a new bridge at Bottletop Bridge site on Highway 5 (December 5, 2021); d) a double-triple temporary bridge at Falls Creek (January 19 2022); ©BCMoTI.

6.3.2. Recovery from a flooding event in Switzerland

The flood of August 2005 in Switzerland is extraordinary in recent times, but in historical retrospect it is not unique. It was caused by so-called “Vb cyclone” weather pattern (Figure 6.11). After the weather development had still been underestimated on August 21, the second storm warning on August 22 announced the full extent of the precipitation. At this point, massive damage had already occurred in some places. In other places, the emergency measures have been already taken.

a) b)

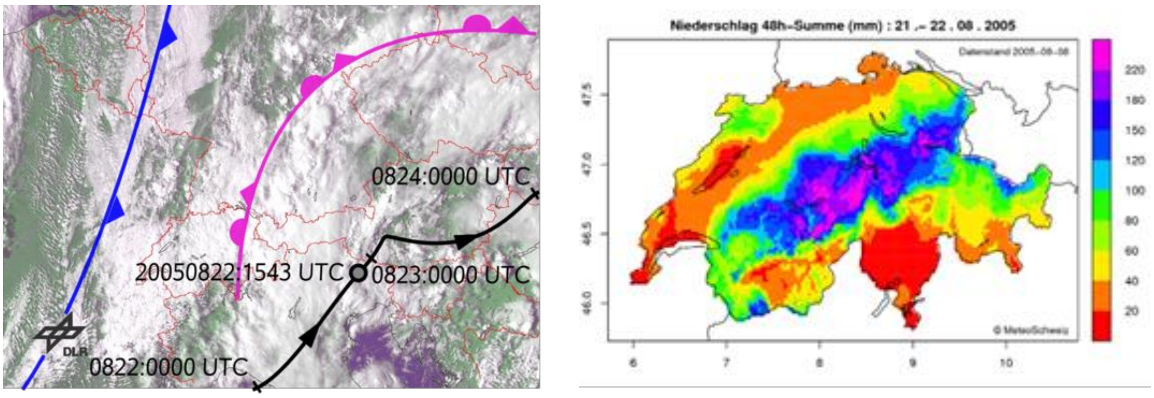


Figure 6.11 Occurrence of a flooding hazard in Switzerland, 2005; a) Weather pattern, ©DLR; b) precipitation quantity (mm of rain in 48h); ©MeteoSchweiz.

In the case of Melchaa railway bridge in Sarnen, the railway traffic was stopped over the bridge in a timely manner. The creek Melchaa reached 300-year water level and the railway steel bridge, constructed in 1933 was pushed downstream (Figure 6.12a). Given the importance for the local economy the railway connection was provisionally replaced by buses. At the same time the provisional bridge was constructed and opened for service in September 2005 (Figure 6.12b). In July 2008, the new posttensioned concrete bridge (Figure 6.12c) was opened for traffic. During construction the railway traffic was only minimally interrupted.

This case study is interesting from different resilience aspects:

- Due to emergency warning – although it could have been more in advance – the traffic was stopped, and possible casualties were avoided. The resourcefulness of weather forecast played here an important role.
- In aftermath of event the bus traffic replaced railway traffic, but at the same time in only five weeks the temporary bridge was built, and the functionality of the railway infrastructure was reestablished. This emphasizes the importance of rapidity of response and resourcefulness aspects (temporary solution + traffic interchangeability).
- Subsequently, the new bridge was built maintaining the provisional bridge and ensuring redundancy. Finally, the traffic was redirected to the new bridge and provisional one was deconstructed.

Apart from this isolated replacement project in aftermath of 2005 event, extensive measures are undertaken in Switzerland starting with improved weather forecast service, improved risk maps and numerous strengthening measures on infrastructure.

a)

b)

c)

Figure 6.12 Damage and recovery due to cyclone event in Switzerland; a) the failure of a Melchaa rail bridge, @Civil Engineering Office in Kanton Obwalden; b) the provisional bridge, ©dsp.ch; c) the new post-tensioned concrete bridge, ©dsp.ch .

6.3.3. Bailey Bridge Services in New Zealand

Waka Kotahi's Bailey Bridge Services contracts in New Zealand provide an approach to emergency bridging that is not typically seen in other countries, where deployment of temporary bridges is used to restore access. This solution is a unique service, which is invaluable against New Zealand's rugged terrain with limited network redundancy. Where regional communities could become isolated following disaster, deployment of Bailey bridges is a relatively quick, well understood process and able to open up access routes in a matter of days.

The Bailey bridge services contracts are strategically important for emergency response as recently demonstrated following significant flooding (Figure 6.13) and landslide events (Figure 6.14). Additional benefits of this highly adaptable system include use as construction site access, vehicle bypass over or adjacent to damaged/deteriorated bridges, temporary works and temporary access for events. Bailey bridges have been used successfully in New Zealand as both temporary and permanent structures, for the following:

- Replacement of collapsed bridges (between 3 m and 200 m long),
- Restoring access to roads washed out in storms,
- Providing cost-effective temporary structures for roading projects, and
- Providing minor stream crossings for movie locations and other non-emergency situations.

a) b)

Figure 6.13 Response to a bridge failure due to scour, Arapata Road, Manawatu District Council, 2015; a) the bridge failure; b) the installed Bailey bridge; ©NZTA.

Figure 6.14 Application of a Baily bridge at a landslide site on the Mahia East Coast Road, Wairoa District Council, 2019; ©NZTA.

The Bailey Bridge Services contracts have been running in their current form for over 20 years [65]. The contracts are self-funding and are currently operating efficiently. The services project runs on commercial principles with all costs relating to the storage and maintenance of the Bailey bridge stock being offset by a hire revenue. A Bailey bridge is a versatile, modular form bridge system that is relatively quick to erect and dismantle. It provides single-lane vehicle access for temporary or semi-permanent use. The basic component of a Bailey bridge is a three-metre-long truss panel, which can be configured to provide variable span lengths and cater for a range of loads. Waka Kotahi Bailey bridges are available for commercial hire to all interested users, including private companies and individuals. Waka Kotahi owns more than 3000 tonnes of Bailey bridge components. A 30-metre single span Bailey bridge could be delivered, erected and in use within one week. Longer-span bridges may take longer owing to the need to build piers to support them. As inherently flexible, temporary structures, the Bailey bridge does require regular inspection and maintenance including tightening of components while in-service. The bridge stock is currently stored across two depots in New Zealand, one each in the North (Figure 6.15) and South Island. Both Bailey Bridge depots are required to have an emergency stockpile set aside for easy access, consisting of enough components to construct two 10 bay (30 m) Double Single Chord Reinforced (DSCR) Bailey bridges.

Figure 6.15 A storage of Bailey bridge components at a depot in Hastings (North Island), New Zealand, ©NZTA.

Two types of timber components form the Bailey decking system: chesses (timber deck planks), and ribands (timber kerbs forming part of the deck lockdown system). These are considered to be a consumable item of stock due to the deterioration and wear sustained in-service and during deconstruction. Manufacture of additional timber components is undertaken as required, based on regular review of stock levels in each yard.

For the past 20 years, average utilisation has been 18 Bailey bridges in service per year (Figure 6.16). However, it is noted that the two 'long service' Bailey bridges (Raparapariki and SH6 Waiho) together equate to just over 13 'equivalent bridges' in service. The recent peak in utilisation over the 2016-2018 period relates to the deployment of several Bailey bridges in response to the Kaikōura earthquake. These deployments were for temporary bypass during bridge repairs/replacements and alongside one-lane bridges on SH63 to facilitate two-way travel while this route saw increased demand during the recovery period. Recent increased utilisation can also be attributed to increased flood damage and coastal erosion due to frequent severe weather.

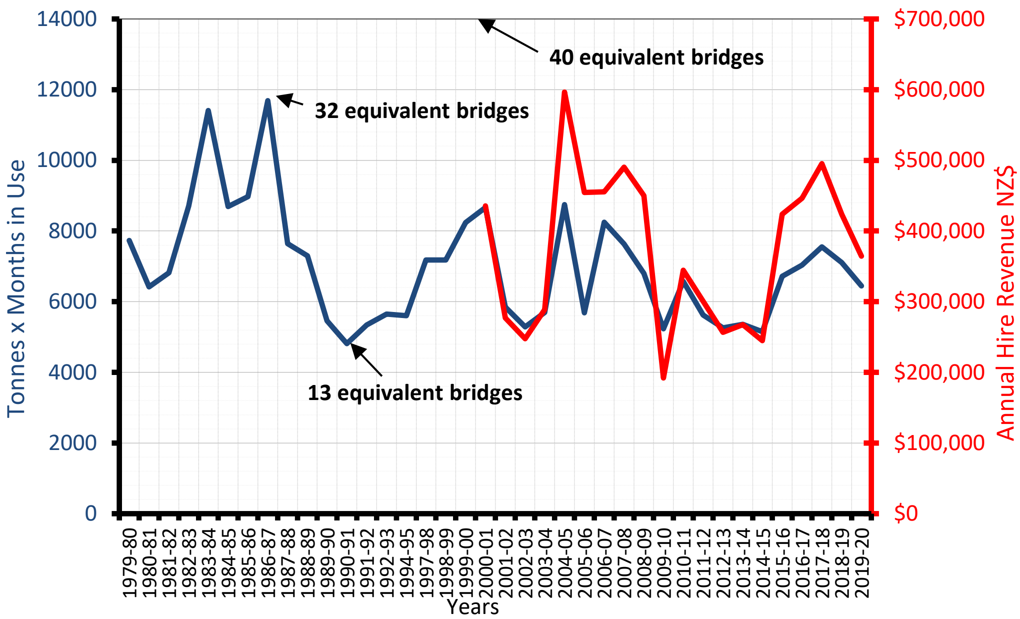


Figure 6.16 Historic utilisation of Waka Kotahi's Bailey bridges, ©NZTA.

As artefacts of the WWII era, Bailey bridge components are no longer produced by reputable suppliers and original components in good condition are difficult to acquire. While the current stockpile is considered to meet the current national need for emergency and temporary bridging, a review is proposed to consider the future strategy for national Bailey bridge stock and services.

6.3.4. Experience with restoration in flooding events in Serbia

The territory of Serbia is vulnerable to various types of natural hazards [66], and the total damage caused by extreme climate and weather events since 2000 is estimated at EUR 5.0 billion. Flooding represents the greatest hazard in terms of total damage and number of people affected, with annual average population affected by flooding of about 200,000 and the annual average affected GDP about USD 1.0 billion, [67].

From 13-18 May 2014, a low-pressure cyclone designated Tamara affected a large area of Southeastern and Central Europe (Figure 6.17a), causing river floods and landslides where Serbia and Bosnia and Herzegovina had suffered the greatest damage. For Serbia it was the worst flooding in 120 years, which affected 119/160 municipalities in western and central parts of the country (Figure 6.17b), affected more than 1.6 million people (of about 7 million inhabitants) and claiming 57 lives. Thirty bridges were severely damaged or collapsed and 50 suffered minor to moderate damage on categorized roads, while more than 200 bridges were affected on local and uncategorized roads, along with 3,700 km of roads affected (total network length 38,600 km), [68]. One of the main problems emanating from the floods included activation of approximately 2000 landslides, out of which 135 have affected the road network, [69].

a) b)

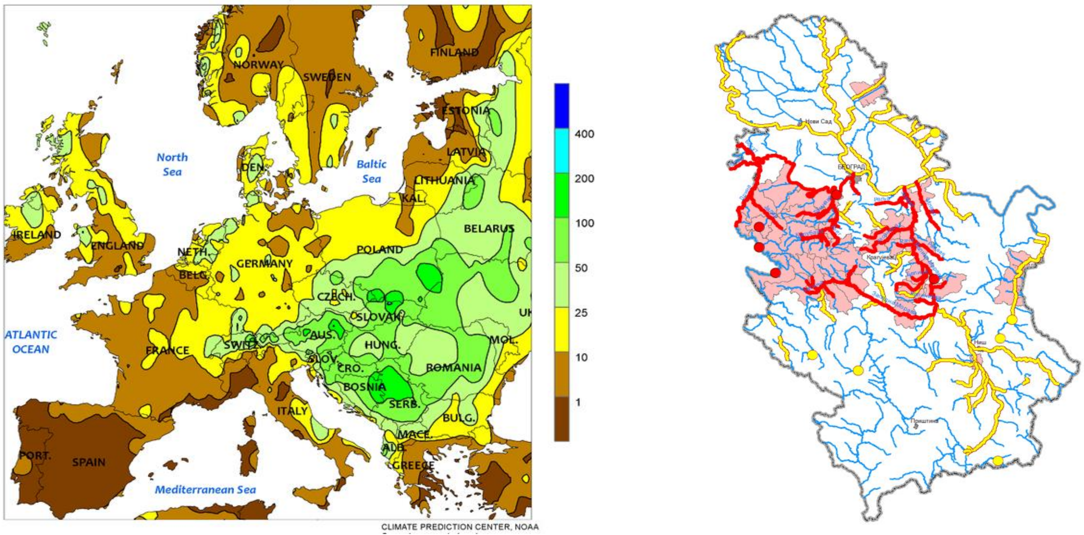


Figure 6.17 Flooding in South-East Balkans in 2014, Europe. a) NWS-NOAA Europe total precipitation in mm, May 11-17, 2014, [70]; b) map of Serbia - affected regions and main roads, [69].

The total damage to transport infrastructure was estimated to EUR 104.4 million. The estimated needs for reconstruction of primary, secondary and local road sections, including bridges and culverts, and remediation of landslides, were EUR 23.5, 30.5 and 34.0 million, respectively [71]. The road reconstruction included measures to improve resilience of road network: improved design of new assets, performing of flood protection works near rivers and enhancing drainage capacity, as well as re-alignment od road sections destroyed by landslides. The recovery lasted until mid-2017.

The funding of recovery was supported by European Commission (EC) and international financing institutions. EC supported through solidarity fund construction of 72 new bridges in local municipalities, reconstruction of 8 road sections in the total amount of EUR 9.8 million. The projects included a few bridges on main roads (e.g., Figure 6.18a), as well as several bridges with smaller spans used mostly for farm access.

a) b)

Figure 6.18. Reconstruction of assets after the flood in Serbia; a) reconstructed bridge on Jadar River in 2017; b) rehabilitation of "Vinjište" landslide in 2018, [69]. .

Through Instrument for Pre-Accession Assistance (IPA), European Union (EU) supported rehabilitation of critical landslides and structures. This included reconstruction of road structures already started under IPA 2012, with a new grant agreement of EUR 10.5 million. dedicated to mitigating damage (mainly landslides) to roads that occurred during the subsequent floods that occurred in March and August 2016 in 17 municipalities. The most affected was the municipality of Bajina Bašta, where at least 100 km of local roads had to be rehabilitated. Also, the project aimed at the remediation of up to 48 critical landslides (Figure 6.18b) and the reconstruction of 14 road structures (bridges and retaining walls).

Following the flooding events in Serbia, the World Bank (WB) supported establishment of a National Disaster Risk Management Program (NDRMP) to coordinate efforts to boost resilience throughout the country and provided Disaster Risk Management Development Policy Loan to take advantage of the Catastrophe Deferred Drawdown Option (Cat-DDO), [67]. EU and WB supported, creation of high-resolution Digital Terrain Models using advanced LiDAR survey technology to better assess future flood risks in Serbia, thus increase preparedness.

6.3.5. Response to flooding events in Argentina

The impact of climate change has brought significant socio-economic damage to affected regions in Argentina. There has been an increase in number of extreme flooding events, and the forecasts on precipitation and related flood levels, assumed in design phase of road infrastructures, have often been exceeded.

An example where flooding caused dire socio-economic consequences is the failure of a bridge on the Lules River, located 20 km from the capital of the Tucumán province. Between months October to March, abundant seasonal rains are usually registered, that cause the high levels of the Lules River and consequent related issues in the nearby cities. However, the constant rains in the summer of 2015 generated unforeseen, extreme floods in the province, with significant impacts on the road infrastructure. In the beginning of March 2015, this event resulted in riverbed erosion and scour that undermined the abutment of a bridge located on the State Route No. 301 (Figure 6.19a). Due to this failure, the access to the capital had to be organized via detours. The additional travel distance amount to 25 km resulting in additional travel time of 30 min. The repair of the bridge lasted for 5 months.

Another example is the occurrence of a rain event that affected town of Santa Victoria Este located on the banks of the Pilcomayo River (the province of Salta). From December 2017 to the beginning of February 2018, the daily precipitation data, showed that it rained every week, exceeding the average values of the maximum precipitation in three events, adding almost 600 mm of accumulated precipitation. Along State Route No. 54, various transversal drains were designed for an extreme discharge from a rainfall. However, one of the culverts failed due to an unforeseen volume of runoff water (Figure 6.19b). As the State Route No. 54 is the only connection with the rest of the country, the town was isolated. Additionally, the rain raised the level of the Pilcomayo River, which caused the flooding of the town, additionally hindering the evacuation. The authorities of the state of Salta sent helicopters with essentials until the road was reconstructed after 45 days.

a)

b)

Figure 6.19. Flooding damage in Argentina; a) failure of a bridge over Lules river in 2015, [72]; b) failure of road infrastructure, Santa Victoria Este, 2018, [73].

6.3.6. Response to a flooding event in China

In the Shaanxi Province, China, there have been severe damage and high losses due to natural hazards that have rapidly increased over the years, especially due to flood disasters along the rivers in mountainous areas. In this province, there are 24 provincial highways and 8 national highways of which the highway G108 represents an important route to the southwest of Sichuan. This highway was constructed along the Heihe River in the northern foothills of the Qingling mountains. From 5pm 28 July to 8pm 29 July 2011, a heavy rain fell in Qingling mountains. The rainfall rose to 200mm/m^2, which caused severe damage to the highway. There were four sections of whole-width damage to the subgrade (*Figure 6.20*), five sections of half-width damage to the subgrade, 24 sections with damage to lower retaining walls and 76 sections of damage to the pavement. Traffic disruption lasted for one whole month and economic losses were at least RMB 38 million.

Figure 6.20 Whole width flood damage to highways in Shaanxi Province, China, [74].

7. RESILIENCE APPROACH IN ASSET MANAGEMENT

7.1 Overview

The preservation of transportation infrastructure in the face of natural hazards is paramount to insuring the mobility of people and goods. The preservation measures require increased investments to cope with the expansion of roadways and ever-growing traffic count and traffic loading. Transportation agencies as owners/operators of infrastructure are constantly under pressure to perform cost-effective maintenance. Transportation asset management is a network-level activity that involves supporting and managing the function of assets over their lifetime. This involves the application of new materials, technologies and management procedures.

As outlined in Chapter 2, transportation agencies are on route to or already adopted risk-based asset management programs to mitigate the threats and related failures that can cause disruptions. This includes identifying threats, improving existing infrastructure to accommodate traffic and climate expectations, adding redundancy to the network via building alternative routes, asset relocation to avoid exposure to high magnitudes of threats, applying robust maintenance solutions, etc. By timely performing such activities, the resilience of the network to threats is definitely improved. However, threats may still occur and compromise the desired level of service, thus agencies need to be prepared for such circumstances and be capable of performing a rapid response to contain the extent of consequences to stakeholders. So, risk-based approaches are being expanded with activities that foster short-term planning, which relates to increasing preparedness in the face of failures and expediting recovery if the failures do occur.

Perhaps the most important aspect of resilience is resourcefulness, as it relates to all other aspects. Besides enabling sufficient materials, machinery and funding above all, building on human resources may be of a decisive role in improving resourcefulness. This includes asset management training for staff to ensure that they have the necessary skills to contribute to the overall asset management strategy of a transportation agency. When disruptions occur, effective data recording and management are vital. Properly managed incident data forms the foundation for proactive measures as it allows agencies to learn from past events and adjust their maintenance/recovery strategies accordingly. Further, improving resourcefulness needs to be backed up with an asset management system and various decision-making tools. The tools are used to identify threats, analyse failure scenarios and consequences and estimate optimal requirements on resources and maintenance of assets, which accommodate the needs of stakeholders, and thus justify the benefits of investments in the transportation sector. Implementing a resilience-based approach within asset management is of paramount importance in the face of various threats to transportation infrastructure.

In this chapter several examples of agency-wide approaches are presented, to demonstrate that transportation agencies are already on route in the implementation of methodologies that focus on resilience aspects in decision-making. In the focus is utilization of geographic information system (GIS) tools to identify potentially vulnerable areas to threats and further rating of assets to estimate the urgency of measures. The importance of dedicated budgets for risk reduction and mitigation measures is emphasized.

7.2 Agency-wide approaches in addressing resilience of road networks

7.2.1. Colorado Department of Transportation resilience program

The Colorado Department of Transportation (CDOT) Resilience Program is an initiative to improve the resilience of the state's transportation infrastructure and operations. The program aims to ensure that the transportation system can withstand and recover quickly from unexpected events and challenges, such as natural disasters (floods, high winds, avalanches, rockfalls).

Resiliency became a priority for CDOT after a 2013 flooding event along the Front Range caused severe damage to the state's roadway network, impacting roughly 500 miles of road (approx. 804 km) and 50 bridges, and requiring more than US$ 700 million in emergency repairs, [75]. In response to this event, CDOT began assessing its risk to threats in order to better prepare the transportation system in advance. In 2018, the Transportation Commission adopted Policy Directive (PD) 1905.0 “Building Resilience into Transportation Infrastructure and Operations” [76], which directs CDOT to support state resilience goals by incorporating resilience in strategic decisions about transportation assets and operations. This proactive management of threats minimizes the resources needed to rebuild and restore service, minimizes disruptions to people's lives and business activity, and lowers the cost to CDOT and transportation users in the long run. National research on disaster damage and federal government spending suggests that every US$ 1 spent on pre-disaster preparedness is worth US$ 6 in terms of future damage it mitigates.

Determining asset criticality is considered as the first step of CDOT’s approach, and it is driven by two primary factors. The first is the resource limitations – i.e., there is no sufficient resources to bring every asset to the highest standard to withstand every potential hazard type and every magnitude of a hazard. Second is the relative importance of CDOT assets, which is vital for evaluating risks and planning across the transportation network. Through several iterations involving diverse criteria and their respective weights, criticality is estimated to aid in comparing mitigation options, identifying areas needing urgent response plans, and recognising alternative routes when crucial links are highly susceptible to failure. The set of six criteria that is considered are: Average Annual Daily Traffic (AADT), AASHTO Roadway Classification, County-level Freight value per Ton, County-level Tourism revenue, Social Vulnerability Index (SoVI) at the county level, and system redundancy, [77]. The considered mitigation measures relate to strategic preparation for future events, efficient response when events occur and remediation of assets and the surrounding environment in the aftermath of an event. The program is an important part of CDOT's overall asset management strategy. This approach aligns with the purpose of asset management as described in Policy Directive 1609.0, [78]. The CDOT has defined three key aspects for considering risk and resilience in its asset management program:

- Enterprise Risk Management. An approach to managing risk across various levels—including agency, programmatic, and project/activity levels.
- Defined Risk Process. The development of CDOT’s risk register to establish risk-management priorities across the Department, and
- Risk and resilience as part of life-cycle planning and life-cycle cost analysis. A comprehensive decision-making process that includes risk management and resilience as a part of budget setting and treatment selection. This also applies to the identification and treatment of twice-damaged assets.

U.S. federal regulations (23 CFR 667) require states' departments of transportation to conduct periodic evaluations of assets that have repeatedly required repair and reconstruction due to emergency events, [79]. To meet these requirements, CDOT maintains and updates a database of damaged assets where it identifies and track twice-damaged pavement and bridge assets. This is done based on the reviewing affected pavement segments and bridge failures within geographic boundaries of each emergency event, reviewing repair projects, and comparing this information to a list of projects funded by emergency response budget.

CDOT has been using the support of GIS tools, with the aim to bring consistence in resiliency planning and making resilience part of everyday agency activities (Figure 7.1). GIS has a relevant role not just in visualisation of asset exposure, but also in consideration of factors like traffic volume and freight value, to determine the criticality of infrastructure thus help prioritise measures, and additionally, to raise the public awareness on the risk of threats and preventative measures. In the context of the report, the main impact of this approach is on increasing robustness and redundancy and related resourcefulness.

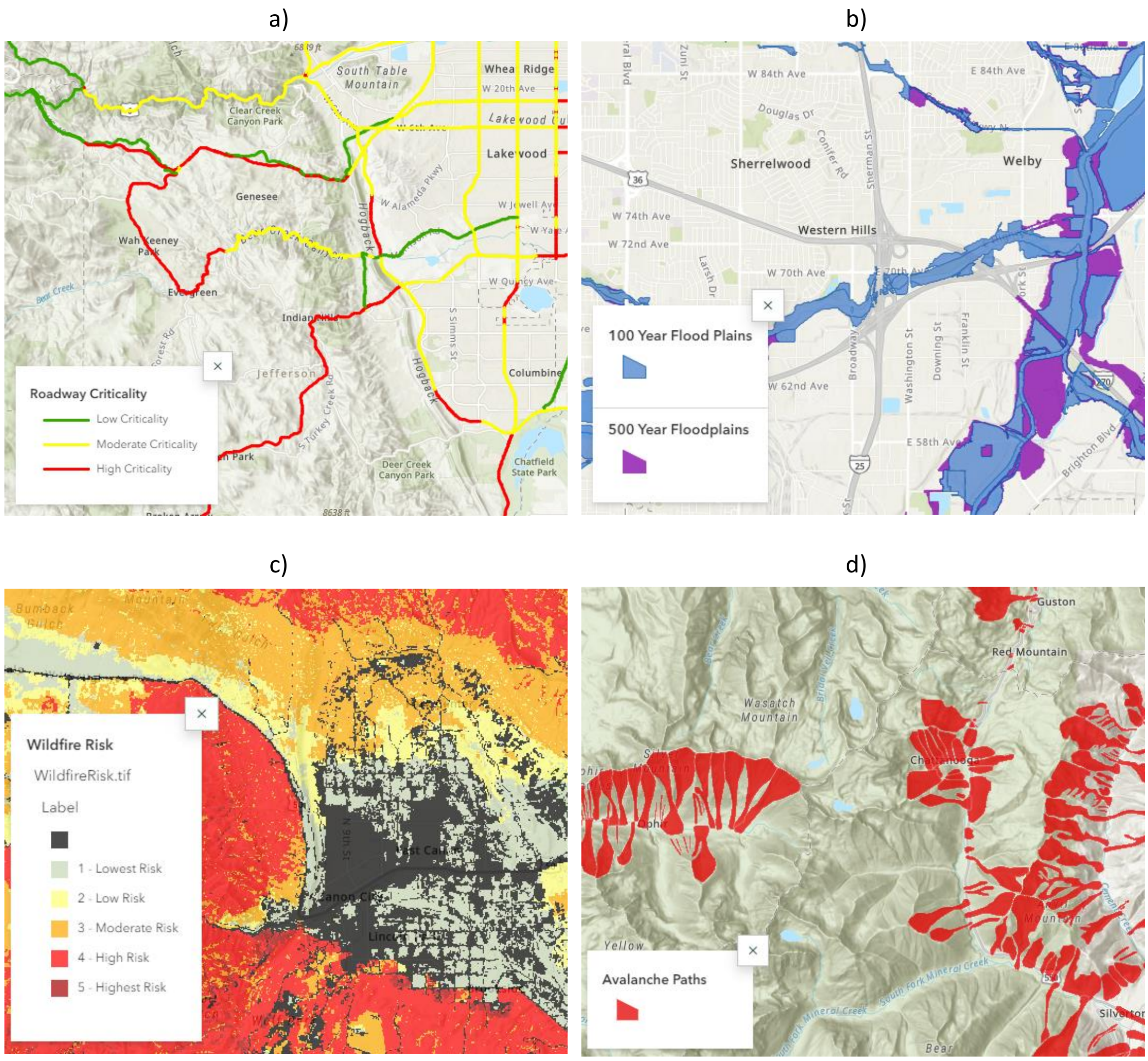


Figure 7.1 CDOT Resilience StoryMap (GIS); a) Roadway Criticality; b) Colorado Flood Plains; c) Wildfire Risk; d) Avalanche Paths; [80].

7.2.2. New Zealand Transport Agency resilience approach

The Waka Kotahi New Zealand Transport Agency (Waka Kotahi) amended Statement of Intent 2018-22 (ASOI), [81]. This document outlines a series of commitments that Waka Kotahi needs to make to support a land transport system that keeps people safe, is connected and can be accessed by everyone. A key component of the ASOI is the eight position statements, which address how Waka Kotahi will respond to the significant challenges that lie ahead for the land transport sector over the next four years. One of the position statements is directly related to resilience:

"The resilience of the land transport system is increased by managing risk and long-term resilience challenges and helping communities recover quickly from disruptions."

The ASOI also sets out two key resilience targets that Waka Kotahi is aiming for by 30 June 2021:

- A system that is recognised as appropriately adapting to climate change and
- Reputation as highly responsive to significant disruption.

The ASOI notes that addressing resilience and achieving the related targets would require a cross-government partnership approach, including:

- an increased understanding of hazard risk, system vulnerability, best-practice response and community tolerance,
- working together to reduce the impact of disruptive events (increasing robustness and redundancy), and
- a decision-making framework that appropriately values the wider benefits of a resilient system.

To better prepare for unknown risks, Waka Kotahi has developed an overarching Business Continuity Plan (BCP), [82] and each maintenance contract has developed an "Emergency Procedures" and "Preparedness Plan". A key purpose of the BCP is to provide a database to inform and support an enhanced capital works programme. The BCP is intended to cover:

- Extraordinary events,
- Major outages, and
- Significant adverse consequences.

The two key elements of Waka Kotahi BCP encompass:

- Reduction – identifying and analysing long-term risks to road users from natural or man-made hazards; taking steps to eliminate these risks where practicable and where not, reduce the likelihood and the magnitude of their impact, and
- Resilience – the actions taken overtime to reduce the vulnerabilities on the network and reduce the impact of events on critical assets. This is a continuing focus to increase the ability of the infrastructure to withstand external forces and limit immediate damage through appropriate upgrading programmes, such as seismic strengthening, and sea protection measures (i.e., increasing robustness and redundancy).

7.2.2.1. Resilience framework

In April of 2020, as part of National Resilience Project Business Case (PBC), Waka Kotahi released its Regional Risk Assessment Summary. The National Resilience PBC aimed to provide context, initial evidence, coordination, priority and initial direction to interventions and activities seeking to improve New Zealand's land transport system's resilience. A report was developed that details the outcome of a Portfolio Risk Assessment (PRA) completed across New Zealand's land transport system. The Portfolio Risk Assessment (PRA) methodology approach consisted of:

- compiling background information to provide a consistent evidence base for identifying hazards,
- completing a desktop evaluation of resilience-related risks based on hazard and asset data and other relevant resilience-related documents,
- testing the preliminary analysis and identifying key risk locations at a regional stakeholder workshop,
- utilising available hazard information, and
- developing initial 'response' options with stakeholders for priority risks, drawing on stakeholder knowledge, and recommending next steps (decreasing recovery and enhancing resourcefulness).

The potential approaches to developing a response included if the risk

- is current and requires a response now,
- is current but can be addressed as the opportunity arises e.g., during projects undertaken for other purposes (safety, efficiency) or as part of emergency response and recovery, and
- will emerge in future so a response can be designed and implemented later.

The three options for responding:

- Defend - develop solutions to mitigate the risk of disruption, for example, flood protection or slope stabilisation,
- Accommodate - plan for periodic disruption, for example providing for rapid reinstatement (decreasing recovery time), detour routes and/or timely information, and
- Retreat - reroute journeys away from the impacted corridor (increasing redundancy).

The benefit of this approach is that it will quickly and transparently provide a shortlist of options qualitatively - allowing appropriate effort to be focussed on those alternatives/options, which merit more detailed development through subsequent business case phases, thereby eliminating options that are unlikely to meet investment objectives or alleviate problems.

The information on natural hazards (e.g., magnitude and frequency), the impacts of specific events and the condition of assets is constantly changing. Failure to account for the increased risk of failures due to hazards is leading to rising costs of unplanned, urgent repairs and emergency works. Waka Kotahi figures showed emergency works spending had increased from approximately NZ$ 30.0 million in 2014/15 to almost NZ$ 79.0 million in 2017/18 and just over NZ$ 72.0 million in 2018/19. The costs of repairs, even in case of extreme events such as an earthquake, are rising as a result of increasing pressure on the transport system (traffic demand and route availability) combined with increased natural hazard occurrence rate. The broad options are to:

- Manage the demand on the transport system (e.g., by mode shift or changes to user behaviour),
- Increase supply, and/or

- Increase efficiency (e.g., improve how we use current investment, response and recovery processes).

Waha Kotahi is currently undertaking a project to identify risks to the land transport system which can form projects for delivery in the next National Land Transport Programme. The project is expected to identify actual points on the network where the risk warrants either a Low-Cost / Low-Risk project or a more detailed investigation.

7.2.2.2. Low Cost-Low Risk Resilience approach

The Low Cost-Low Risk roading improvements fund is available to the Waka Kotahi and local council road controlling authorities to provide for small projects (low cost – under NZ$ 1.0 million to be increased to NZ$ 2.0 million in 2021) that can be implemented quickly (low risk) and are aimed at preventing or mitigating an incident or event impacting on the serviceability of the road network. The prioritisation methodology is based on two criteria, firstly the likelihood of an event/incident occurring and secondly the consequences thereof. The likelihood of each scheme is ranked as either “High”, “Medium”, “Low” or “not supported”. The consequences are considered in terms of three factors and all of them carry equal weighting in the ranking process:

- Benefit-Cost - the costs of doing the work now against the costs of doing the work at the time when the failure/event occurs,
- Safety Risk - the risk to the safety of the road user due to the potential failure/event happening, and
- Disruption - the disruption to route security that would be caused by the failure or event happening.

The overall numerical ranking takes into account the individual ranking of all three abovementioned factors, which carry equal weighting in the ranking process and is best considered using a typical decision-making matrix.

The Low-Cost Low-Risk programme delivers small, quick, but valuable improvements to resilience in a much shorter timeframe than other more costly and longer-term large-scale projects (e.g., see Section 3.3.2). They are important to customers as they can help deliver real improvements quickly and can often buy more time before a larger-scale improvement is required. There are some risks associated with implementing the Low Cost-Low Risk programme, including

- potential, sub-optimal investment decisions made for emergency repairs and low-cost investments, locking in a non-resilient investment, and
- approving a significant number of “low-cost, low-risk” programmes without understanding the wider context and whether these programmes are actually addressing the core issue.

Waka Kotahi continues to refine its processes for Low Cost-Low Risk projects, including reviewing the prioritisation process focussing more on the consequences than the likelihood and the use of technology platforms for ease of application and spatial mapping of threats. A recent innovation has been the development of a detour routes tool, [83], intended to be used by road controlling authorities, authorised contractors and emergency services.

7.2.2.3. Rockfall Hazard Rating system

Waka Kotahi had adopted the Rockfall Hazard Rating (RHR) system, originally developed for the Oregon State Highway Division [84], to rapidly classify rockfall hazards. It was subsequently adopted by several states in America and Canada and is internationally recognised as the state of the art for quick ranking of hazardous rockfall sites. Waka Kotahi made slight adaptations to the original system to account for New Zealand experience. The national road network in NZ is divided into different management areas, which all use the same rating system ensuring a measure of consistency. The RHR system is intended as a proactive hazard management tool rather than a complete assessment guide. The RHR is a "first cut analysis" to allow resources to be directed towards the sites with higher risk for further assessment and/or physical works.

The RHR is a semi-quantitative scoring system that allocates points to the potentially endangered sites depending on road features, geological characteristics and event characteristics and history. The road features include

- roadway width,
- slope height – rocks on higher slopes have more potential energy,
- ditch effectiveness – the ability to trap falling rocks. the assessment is based on grass or gravel shoulders and small bunds (actual ditches are rare in New Zealand),
- vehicle risk – speed environment of the road, the amount of traffic on the road and the length of the feature, and
- decision sight distance - the average distance that is available for a driver to react to a hazard and stop.

The geological characteristics include

- defect driven – the presence and orientation of defects and the friction available to resist sliding,
- erosion driven – the presence of erosion features and the difference in erosion rates, and
- climate and hydrology – the presence of water, ice jacking and freeze-thaw activity.

The event characteristics and history include

- block size,
- quantity of rockfall per event, and
- rockfall history – if no history, maintenance costs for rock clearing in the area is used.

The funding for treating rockfall sites is part of the wider Low-Cost Low-Risk improvements fund. The rockfall sites are then aggregated into the wider resilience funding request competing against other resilience-type projects, such as those addressing flooding and scour. Rockfall mitigation measures can broadly be categorised as engineered measures and non-engineered measures, which increase robustness aspect of resilience. Engineered measures are interventions that either reduce the occurrence of rockfalls or reduce their impact (see Section 3.3.3). Measures such as relocation of the road away from the threat are not realistic to consider as part of a Low-Cost Low-Risk solution.

7.2.3. Canada's adaptation practices

Canadian transportation systems are vulnerable to both extreme weather events and the incremental impacts of a changing climate. Extreme weather disrupts and delays urban travel by washing out roadways and transit routes, and by damaging the electrical and communications systems upon which these modes rely. Increased temperatures cause pavement rutting, buckling of rail lines, and damage to infrastructure built on permafrost in Northern communities. These and other climate risks can affect the cost, efficiency, and safety of urban transportation networks. Canada is growing increasingly urban. In the 2011 national census, 81% of Canadians indicated that they lived within medium or large population centres. The deteriorating condition of municipal infrastructure further complicates the ability of Canada's high-growth and increasingly dense cities to accommodate a growing population. The 2016 Canadian Infrastructure Report Card (CIRC), which assessed the condition of Canada's municipally owned infrastructure, graded 14% of sidewalks, roads, and bridges, as "poor" to "very poor", with a total replacement value of CA$ 50.4 billion, [85]. Several strategies can be used to reduce the impacts of observed and anticipated changes in climate and extreme weather on urban transportation systems. The strategies fall into the following general categories:

- Investing in more resilient materials, infrastructure, and operational practices for transportation infrastructure,
- Improving redundancy within transportation networks – this refers to the availability of multiple paths or modes for urban travel with similar user costs,
- Updating the climate design criteria used in engineering standards to better reflect future conditions (increasing robustness),
- Improving land use policies and controls (e.g., zoning amendments or construction requirements in vulnerable areas), and
- Enhancing the resilience of communities to extreme weather and climate effects through social adaptations.

Adaptation strategies can be placed into the following five categories, according to their type of intervention:

- Disaster Risk Management (strategies involving the revision of emergency procedures based on climate-related impacts, assessing organizational risk using software, and adapting spatial and land-use controls for climate effects),
- Spatial and Land-use Adaption, including the change in land-use and infrastructure approaches in vulnerable areas due to past or expected climate impacts (i.e., increasing robustness),
- Structural and Physical Adaptions (engineering solutions to bolster urban transportation resilience. In northern cities with permafrost, costly methods like stabilizing embankments and permafrost removal are used),
- Institutional Adaption (altering transportation agencies' service delivery and maintenance, e.g., if rail lines buckle, temporary service or speed reductions ensure safety, [86]), and
- Social Adaption (e.g., leverage social networks for better awareness and response during extreme events).

Canada's climate risks and adaptation practices emphasize redundancy in routes and modes for resiliency. "Low-regret" adaptation strategies gain government and community support. High initial costs of adaptations, especially structural ones, and complex urban contexts pose challenges. Collaboration among different sectors is crucial for successful climate adaptation in Canada's transportation networks.

The following examples are related to specific practices and locations where structured approaches were put in place addressing resilience.

7.2.3.1. Coastal erosion inundation

Many maritime cities in Canada have already begun experiencing climate-related impacts. In Moncton, New Brunswick, Canada, the frequency of flooding from extreme storm events and changing tidal patterns has increased over the past decade, [87]. Moncton is located at the nexus of the Petitcodiac River and the Bay of Fundy, a region that experiences one of the largest tidal ranges in the world. The region is also expected to experience gradual sea-level rise and significant precipitation and temperature increases by mid-century, [88].

Specific recommendations for the City of Moncton emerging from the Regional Adaptation Collaborative program (RAC) exercise, were to:

- Develop new arterial roads to avoid low-lying areas and the floodplain of the Petitcodiac and its tributaries,
- Elevate new roadway and bridge infrastructure to ensure access to essential services during extreme weather events,
- Flood-proofing major roads at vulnerable elevations to minimize flood-related damage and ensure rapid system recovery, and
- Mandate higher flood elevations in future transportation planning decisions. A minimum elevation of 10.5 m was proposed to reflect the 100-year flood event line the region is likely to experience by 2100, informed by floodplain mapping.

The goal is to reduce or eliminate damage by providing protective physical barriers to climate stressors and extreme events and thus increasing robustness. This may include hard structures such as seawalls or revetments and soft strategies such as beach nourishment and vegetation plantings. Protective strategies keep water away from infrastructure or provide resistance to the damaging forces of water and waves.

7.2.3.2. Increased snowfall

Whitehorse is the capital of northwest Canada’s Yukon Territory and a significant regional transportation hub. The city relies heavily on the Alaska Highway for external connectivity. In recent years, Whitehorse has experienced highly variable precipitation, including many winters with above-average snowfall. Local officials identify highway obstructions and washouts during extreme weather events as a key concern.

To address these concerns, the City of Whitehorse participated in the development of the community-based climate change adaptation plan in 2011, [89]. Suggested adaptations for urban transportation include establishing annual budgets aimed at managing climate change concerns, expanding the use of road monitoring stations, conducting exploratory feasibility studies of automatic road de-icing techniques, and increasing the porosity of road surfaces to improve re-charge following precipitation.

These adaptations include both “low-regret” and “no-regret” measures. For example, when road improvements are required due to the lifecycle or condition of the infrastructure, the Plan suggests that the city upgrade water and sewer systems accommodate larger stormwater flows. A “no-regret” adaptation on the operational side involves proactive early-spring inspections of drainage to identify frozen storm drains and reduce flood risks.

7.2.3.3. Community adaption plan in British Columbia

The City of Prince George, located in the interior of British Columbia in Canada, is home to approximately 76,000 people. The city has a wide range of transportation modes, including rail, inland marine, and urban transit. While the City's transportation network faces a number of risks from climate change, warmer winter temperatures are likely to have the greatest impact, primarily due to increased freeze-thaw cycles, rain-on-snow events, and freezing rain. Prince George developed several transportation-specific climate change adaptations in 2012 (e.g, [90]), in recognition of the risks flooding poses to roads, active transportation infrastructure, and rail facilities. This was done in the context of a larger community adaptation plan.

A steering committee composed of local practitioners and experts from academia (to balance local needs with best practices) identified 23 forward-looking adaptation actions, in the areas of infrastructure, operations, emergency response and safety, and financing. Through the process, the city also identified some ongoing initiatives that fall under the umbrella of climate adaptation. These included snow and ice control, salt management, road elevation, and dyke construction.

Prince George is now focused on implementing action items in key areas, with promising early returns. The city has begun to aggregate climate data and procedural information to better inform road maintenance decision-making, including data on vehicle and climate interactions.

The transportation component was considered successful by practitioners, given the high degree of public interest in mobility issues, the practical nature of the solutions that were explored and the clear potential for significant cost savings. Prince George adaption strategy demonstrates how communities can successfully incorporate rigorous climate analysis into vulnerability assessments, shifting the discussion from a general recognition of risks to the identification of explicit actions.

7.2.3.4. Rockfall response planning

The section of Highway 99 between the cities of Vancouver and Whistler in British Columbia, Canada is known as the "Sea to Sky Highway". The route was first paved in 1966 as a two-lane roadway carved into the Coast Mountains directly adjacent to Howe Sound. While beautiful in terms of scenery (Figure 7.2), the highway was also dubbed the "Drive to Die Highway", where dangerous driving accounted for 40% of vehicular crashes. Besides, it is frequently being affected by rockfall hazard (Figure 6.1).

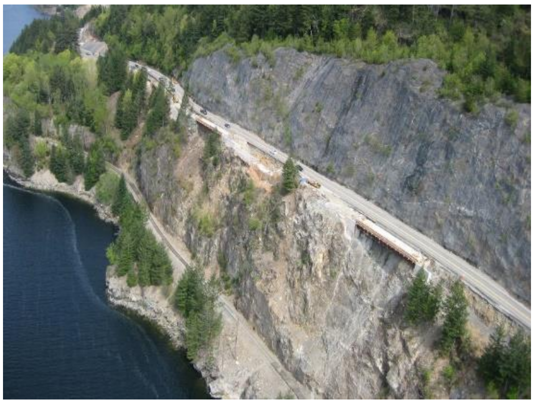


Figure 7.2 Challenging roadway conditions in "Sea to Sky Highway", British Columbia, Canada; ©BCMoTI.

When the City of Vancouver was awarded to host the 2010 Winter Olympics in 2003, the highway underwent a CA$ 775.0 million to upgrade including the construction of

- 48 new bridges and interchanges,
- 219 mechanically stabilized retaining walls,
- 2.4 million m^3 of earthwork and 450,000 metric tonnes of asphalt paving, and
- 20 km of additional passing lanes, 16 km of new median barrier and 10 km of widened shoulders, for improved safety to accommodate cyclists.

The work was awarded to a consortium as a part of a public/private/partnership for the upgrade construction along with operations and maintenance in a 25-year concession contract. As part of the concession agreement, the Province of British Columbia implemented detailed asset preservation performance measures (APPMs) for the following asset classes:

- Highway running surfaces (10 subcategories),
- Structures including (56 subcategories):
  - Bridges and major retaining walls,
  - Major culverts and tunnels, and
  - Major sign structures
- Drainage and debris control structures (9 subcategories), and
- Electrical control systems

As a part of the on-going management of significant rockfall and debris risks to the highway (Figure 6.1), the province has established a risk management and recovery program which includes:

- Inspections following significant natural events (earthquakes, rainstorms and snow)
- Logging of inspections and issues including:
  - Minor debris removal record,
  - Rockfall notification,
  - Major debris removal report, including rock fall hazard report system (RHRS),
  - Slope monitoring report,
  - Slope hazard rating,
  - Unstable slope mitigation program, and
- Identification and prioritization of mitigation procedures to reduce rockfall and debris risk

Each of the program elements is triggered by event criteria, e.g., 100 mm of rain in 24 hours. Once an event is logged, the concession agreement spells out specifics on activities, responsibilities and timing required to return the roadway to a safe operational state.

7.2.4. Protection of the high-volume road network in Austria from natural hazards

ASFINAG infrastructure company is responsible to construct, maintain and operate the high-volume road network of Austria (expressways and motorways). To mitigate risks due to natural hazards for its customers, employees and infrastructure, ASFINAG had developed a strategy (Figure 7.3), which is divided into two branches that deal with:

- prevention of failures (improvement of robustness and redundancy resilience aspects), and
- management of incidents (focus is on the rapidity of response and related resourcefulness)

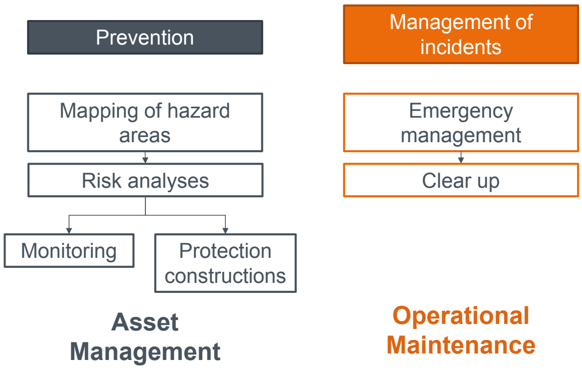


Figure 7.3 Two-branch strategy to mitigate risks of natural hazards to road network in Austria, ©ASFINAG.

Currently, an increasing number of natural hazards is observed in Austria, where the range of annual costs for rehabilitation is EUR 300k-1.5 million. This is less than 0.25% of the annual budget for the refurbishment of the high-volume road network. So far, the availability of ASFINAG's road network has not been much influenced by climate change and the main issues are still related to accidents and roadworks. The plan is to moderately increase the budget for protection structures, thus increasing the resilience of the network.

7.2.4.1. The strategy for the prevention of failures

The main hazards considered are rockfall, landslides, avalanches, wind and floods. The map of natural hazards is elaborated (Figure 7.4), including the pertinent protection facilities, to manage natural hazards with a risk-based approach (Figure 7.5).

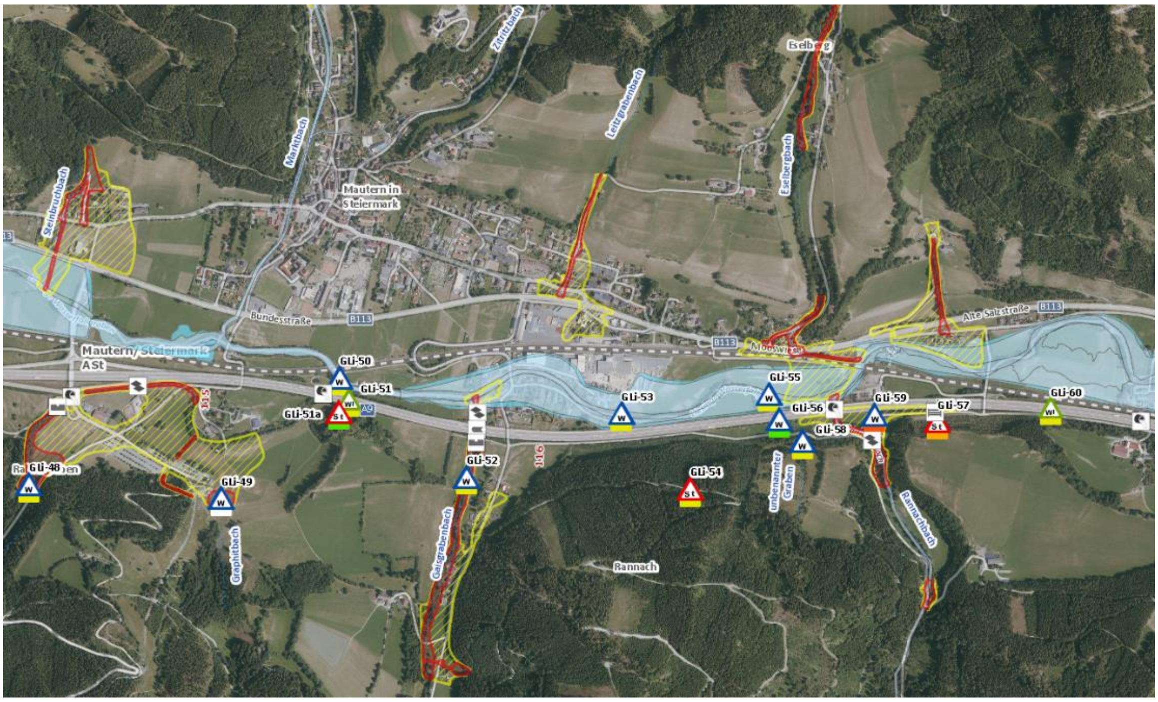


Figure 7.4 GIS map with potential risk and protection structures, ©ASFINAG.

Within the approach, the urgency of measures is classified via hazard potential class and usability of protection facilities class (Figure 7.5a). For classification, the two risk matrices are used. The first one (left in Figure 7.5c) is to determine the hazard potential class GP, via exposition classes (EX) and activity classes (AK) that represent a combination of hazard frequency and intensity. The second matrix (right in Figure 7.5c) is used to determine the urgency of measures class D (see Figure 7.5b), via the beforementioned GP and the usability class (GT) which represents the condition state of protection facilities (if no facility exists, GT is set to the worst grade = 5).

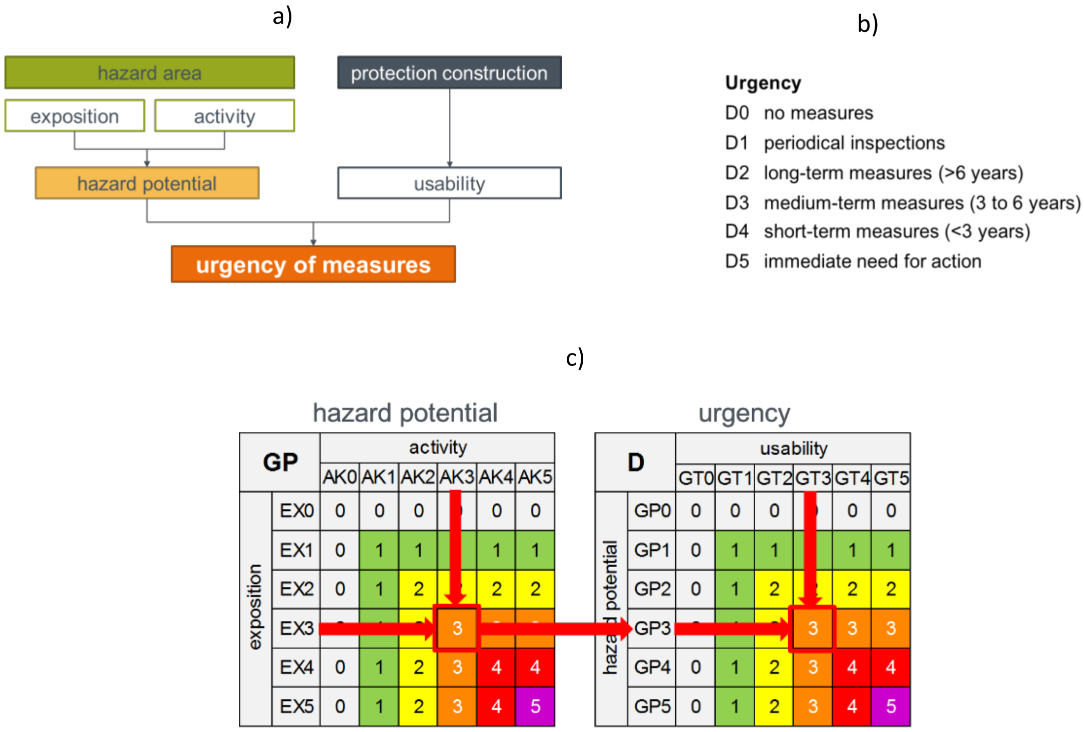


Figure 7.5 Risk-based approach to prevent failures of infrastructure; a) schematics for evaluation of urgency of measures; b) scale for urgency of measures; c) evaluation matrices; ©ASFINAG.

The results of risk analyses are stored in a risk registry for the road network, comprising risk values and urgency of treatments. This information is further considered for prioritization within the annual construction budget. The potential risk spots are marked with triangles as in Figure 7.4 and the colour marking of each triangle corresponds to the colour code used in the matrices for the urgency of measures. The risk spots with urgency class D5 should be treated immediately. The risk spots rated with classes D3 and D4 undergo a risk analysis of the related network section. Where applicable, 3D models of the terrain are used to evaluate the risk for these sections in more detail. Considering the adopted threshold for individual fatality probability of 10^{-5} and a cost-effectiveness criterion, countermeasures are designed for a related road section.

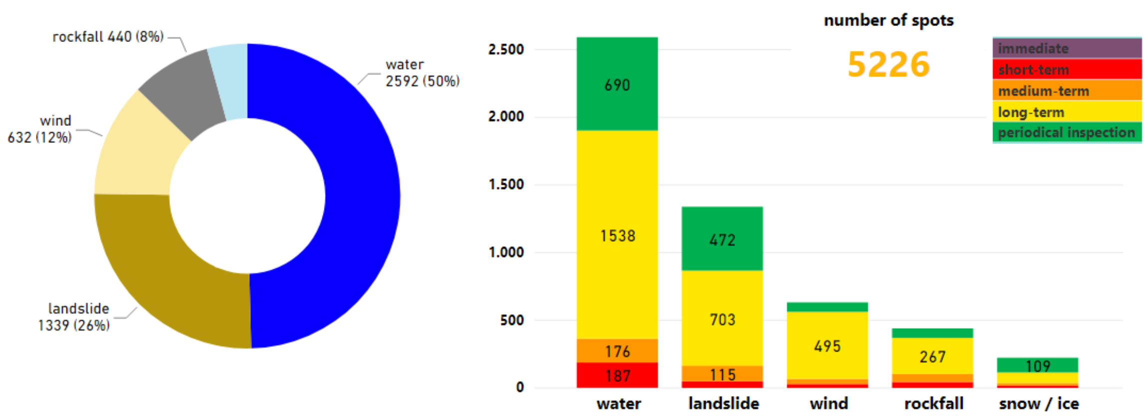


Figure 7.6 Overview of identified risk spots in the road network of Austria, ©ASFINAG.

Until 2020, ASFINAG had detected and categorized 5226 risk spots that need further attention (Figure 7.6). Most of these spots are related to the category water (flooding and landslide) or landslide triggered by slope water. Although climate change was not an issue in the past, it is expected that it will have more impact on the road network in the future, thus ASFINAG is currently planning to invest EUR 2.0 Mil. annually in various, new protection facilities.

7.2.4.2. The strategy for the management of incidents

The main objectives are to minimize the time to react in case of a hazardous event and occurred failure(s) and minimize the duration and extent of closure of the affected road section(s). Depending on the magnitude of an event, this is to be achieved through the following actions: raising the alarm, initiating immediate measures, and assessing and determining any other necessary actions (establishing temporary traffic routes, expert analyses, etc). Therefore, well-defined roles have been established in the company to have clear responsibility and interact seamlessly with local authorities (police, emergency services) in the restoration of normal conditions.

In general, each incident must be evaluated and the roles in the analysis depend on the type and extent of an event:

- Documentation and evaluation: roadway service and the highway engineer, and
- Analysis: ASFINAG experts and if necessary, external experts (geologist, geotechnical engineer, hydraulic engineer, etc.).

Systematic recording of hazard events employing reports, statistical data, photographs and/or plans (sketches) is being performed. To store this data, a database with GIS capabilities will be developed, which will improve future strategies for the prevention of failures and allow for better preparedness in the face of hazards. In the future, data from the event database will be used for the evaluation and analysis of oncoming events (updated probability of event occurrence).

8. CONCLUSIONS

The world is facing unprecedented challenges from climate change, which is increasing the frequency and magnitude of natural hazards that impact transportation infrastructure and societies on the whole. In many cases the related issues originate from existing transport networks and the fact that the hazard key hotspots often geographically coincide with highly populated and economically pivotal areas (e.g., coastal regions and floodplains). Infrastructure owners and operators are increasingly working on innovative methods/approaches to support decision-making in the face of sudden events. The level of development of these approaches differs from country to country with respect to past experience with failures, hazard types and economic strength. It is very common that the initiatives and efforts in the development of resilience approaches and executing preventative activities come only following a recent catastrophic event.

The decision-making in asset management is governed by three constraints: available resources, acceptable risk levels and required road network performance. Agencies responsible for road infrastructure strive to satisfy these, which can be a challenging task, especially in the cases of asset preservations in extreme events. Here, the value of resilience introduces a new dimension in a decision-making, which can account for the uncertainties in a recovery process. A resilience-based approach to support decision making should be understood as a broadening of a risk framework, which is discussed in Chapter 2. Here, the overview of the resilience terminology is presented and shown how the value of resilience can be quantified via evaluation of the performance of road networks. The definition of the resilience and its aspects: robustness, redundancy, rapidity of response and resourcefulness is taken from the preceding PIARC report, and since the resourcefulness implies resource and capacity management, it is in this report broadened to all other resilience aspects. The main similarities and differences between risk-based and a resilience-based approaches in decision-making are highlighted, with the focus on the unique aspect of resilience, which is the recovery phase. The approaches already applied by road owners and operators for assessment of asset management goals, which are based on Key Performance Indicators, and can be used in quantification of the benefit i.e., performance of road networks. The quantification of resilience allows to tailor the measures on assets in both medium to long-term planning e.g., preventative maintenance and short-term planning, e.g., recovery activities after failure(s) occur (Section 2.3).

For some threats, protection of exposed assets via sacrificial structures is a viable solution to reduce oncoming threat magnitudes, while in some cases the reduction of exposure to threats can be achieved by making adaptations at asset micro locations, which is the topic of Chapter 3. Through examples is demonstrated that such solutions may be effective and increase robustness aspect of resilience, provided there is a clear identification of threat scenarios (frequency, magnitude and extent), so the related measures can be applied to a specific location (e.g., a wire mesh in a case of a rockfall) or be network-wide (e.g., preventing a fire hazard by selective cutting of vegetation).

When assets cannot be viably protected from extreme threat magnitudes, the related resistance of assets may be increased, which is the topic of the Chapter 4. It is demonstrated that knowledge on structural weaknesses of assets and pertinent failure modes due to threat magnitudes can be used to retrofit, enhance or strengthen these structures, making them more robust to endure threats (e.g., a seismic loading, a bridge deck uplift in a flooding event). The approaches that imply weakening of elements of a structure and accepting the fact that some damage may occur on assets in such events (e.g., in an earthquake) may sound controversial, but in fact repairing of the damaged elements is deemed more acceptable than rebuilding of the whole structure. Also shown is that a targeted weakening of structural elements may help in containing some failure modes (e.g., due to fatigue cracking), without compromising the asset performance.

The idea of preventative maintenance is to fully eliminate the scenario where assets fail when a threat of a certain magnitude occurs. However, it is not possible to address all threats and assets in this way, especially when transportation networks cover large territories and are affected by different natural hazards or when hazards may happen anywhere in a network (e.g., an accident). It is therefore necessary to be prepared in advance for potential network disturbances that can emanate due to asset failures, which is discussed in the Chapter 5. In the case of critical infrastructures or electro-mechanical equipment, a solution is to enable sufficient redundancy to partially or fully mitigate the consequences of failure to network users and society on the whole. This may not be a big investment in the case of electro-mechanical equipment but can be considerable in the case of building new assets (e.g., detours), thus it is of pivotal importance to maintain and upgrade the current network and increase transportation interchangeability as well. In addition, the demonstrated cases show the importance of increasing preparedness for a failure scenario, by allocating adequate resources within an easy reach that can be activated to foster a quick response if a failure scenario occurs.

It may be the case that all necessary maintenance had been timely performed, but the failures still occurred. Then comes the recovery phase where the affected network should be returned to the pre-failure state (or better), in the shortest time possible and with optimal use of resources, which is the topic of the Chapter 6. When hazards and failures occur, human safety remains the primary concern within disaster affected areas, and transparent emergency activities and well-defined responsibilities are pivotal to ensure a coordinated response. The short-term activities, which relate to issuing of timely warnings and to alert the emergency services (resourcefulness aspect), may have a decisive role in containing the extent of consequences of failures in the recovery phase along with a rapid response (e.g., temporary structures that enable redundancy). The level of all resources (human, equipment, funding) needs to be maintained throughout the recovery phase, to prevent delays and resulting economy and service stall.

Given limited resources for protection/strengthening/building of structures, there is a need for an effective management strategy that enables decision-makers to identify and prioritise assets for detailed evaluations and measures. The focus needs to be network-wide and besides asset properties and prediction of hazard magnitudes need to consider other factors, such as age of infrastructure, increasing traffic demand, deterioration processes, etc. Some countries are already on route in applying approaches, which are based on consideration of risk and resilience aspects, as shown in the Chapter 7. The incorporation of resilience in an agency-wide asset management approach begins with the comprehensive mapping of potential threats, via GIS-based tools that provide a visual representation of vulnerable areas. The presented methodologies highlight the importance of threat classification/rating, which plays a significant role in estimating the urgency/criticality of measures to be applied. As resilience-focused projects necessitate prioritisation, emphasized is the effectiveness of dedicated budgets for risk mitigation measures. This strategic allocation ensures a targeted approach to enhancing resilience.

Engaging stakeholders, including local communities and external experts, in the identification of threats, prioritisation of preventative and recovery measures, is essential for successful resilience integration in asset management. Their contributions enhance a shared mindset on threat/failure awareness and promote data-driven decision-making. By embracing resilience as a core component of decision-making and by drawing insights from established frameworks and examples from practices, road agencies can formulate comprehensive resilience strategies that not only safeguard infrastructure but also foster its durability, sustainability and adaptability in the face of future threats.

The case studies in the report have shown that agencies around the world are already performing various risk-based assessments when planning maintenance in the face of potential threats. Various information is being gathered on threat magnitudes, asset condition and traffic demand, and used to facilitate asset management. A practical recommendation to agencies that would like to consider the resilience in decision making, is to broaden the scope of data collection to a recovery phase. Here, besides the knowledge on recovery duration and measure effectiveness, it is essential to consider temporal demand/consumption of relevant resource categories, both on an agency side (e.g., human, machinery and funds) and user/society side (e.g., water, electricity, food and housing).

The next step in the work of PIARC on resilience topic would be to elaborate a guidelines for resilience improvement. Here, one of the main tasks should be investigation interdependency between different infrastructures for resilience, impacts on communities and the society as a whole.

9. GLOSSARY

The list of terms commonly used throughout the report:

Term	The principal scope	Definition
Resilience/Resiliency	Network	See Section 1.2
Availability	Network	A proportion of time network is open for service (see KPI).
Functionality	Asset	The ability to conduct designed traffic volume (see KPI).
Serviceability	Asset	The quality of being able to provide good service, e.g., related to capacity of road(s) and the ride comfort (see KPI).
AADT	Asset, Section	Annual Average Daily Traffic
Stakeholders	Network	A person, group or organization with a vested interest, or stake, in the decision-making and activities related to business, organization or a project (see e.g., Table 2.1).
Performance/Quality/Benefit	Network	Fitness for purpose of a network to its stakeholders.
PI (Performance Indicator)	Asset	An observation (measured/recorded information) that can be used to measure the performance of an assets.
KPI (Key Performance Indicator)	Network	Values that show whether performance of an asset/network is being achieved. Based on one or more performance indicators (PI).
Vulnerability	Asset	Expected consequences to stakeholders due to asset(s) failure in an event of a specific magnitude.
Demand	Asset, Network	Required KPI/PI threshold(s) by stakeholders.
BCR	Asset	Benefit-Cost-Ratio
GIS	Network	Geographic information system

Acronyms of the road agencies/authorities mentioned in the report:

ANE Administração Nacional de Estradas, Mozambique
(In English: National Roads Administration)

ASFINAG Autobahn and Schnellstraßen-Finanz-Aktiengesellschaft, Austria
(In English Autobahn and highway financing stock corporation)

ASTRA Bundesamt für Strassen, Switzerland
(In English: FEDRO – Federal office for roads)

IP Infraestruturas de Portugal, S.A., Portugal
(In English Infrastructures of Portugal)

NZTA Waka Kotahi New Zealand Transport Agency, New Zealand

BCMoTI British Columbia Ministry of Transportation and Infrastructure, British Columbia, Canada

CDOT Colorado Department of Transportation, USA

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