METHODOLOGIES AND TOOLS FOR RISK ASSESSMENT AND MANAGEMENT APPLIED TO ROAD OPERATIONS

Technical Committee 1.5 Risk Management
World Road Association
The World Road Association (PIARC) is a nonprofit organisation 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 2012 – 2015 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.

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The Technical Committee was chaired by Keiichi Tamura (Japan); Robert Loranger (Canada-Quebec), Yukio Adachi (Japan) and Pedro Tomás Martínez (Spain) were respectively the French, English and Spanish-speaking secretaries.
This report, written by Technical Committee 1.5 on Risk Management, deals with methodologies and tools for risk assessment and management applied to road operations including managing risks in relation to the climate change.

Chapter 1 of this report starts with a classification of methodologies for risk management of road infrastructure. Particular attention is paid to methodologies that can be applied on object level and those at the strategic level. Pre-existing risk management methodologies are presented as examples on the basis of risk matrices developed for this report. Subsequently chapter 1 describes possible climate change related threads and resulting impacts for road infrastructure. This compilation allows owners and operators the identification of possible vulnerabilities and their impacts. Finally, recommendations and options for infrastructure management with regard to the consideration of the above mentioned aspects are presented.

Chapter 2 presents a study on the development of a practical road disaster management system for various natural disasters by applying risk management techniques. Risk is defined here as the product of the likelihood of disastrous event and its consequences. The road facilities targeted are bridges, embankments, tunnels, slopes, and so forth. Various natural disasters such as earthquakes, tsunamis and heavy rainfalls are included in the analysis. Effects of both direct and indirect damage are assumed in the present study. The former includes human damage and the restoration cost of damaged facilities, while the latter includes economic loss associated with traffic detouring. Particular emphasis is put on rating the risks to various road facilities due to different natural disasters by using a common index. The outputs of the proposed system are presented through a risk curve, risk register table, and risk treatment plan, which are readily applicable to road disaster management.

Chapter 3 describes how population and machinery usage has increased in high quantities not without consequences on the planet. As a consequence, extreme weather events occur and the tendency is increasing due to the climate change. This provokes severe damage to road infrastructure due to storms, floods, landslides, strong winds, erosion, droughts, high temperatures and heavy snowfalls. One of the most vulnerable countries in the world to climate change is Mexico and with a case study it is shown that it does not have to be a strong hurricane to produce a disaster, but a tropical storm is enough to cause strong impacts on roads because of the amount of water that comes with it.

Chapter 4 presents a web-based Risk Management Manual, which was developed as a useful knowledge database in order to introduce and disseminate road risk management techniques worldwide. Roads and road traffic are exposed to various risks due to natural and man-made hazards and climate change, and the main purpose of this manual is to foster practice of risk management among the road communities. The proposed Risk Management Manual consists of three components: Toolbox, Archives and Links. It should be released on Internet in 2016.
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INTRODUCTION

Technical Committee 1.5 Risk Management of PIARC comprises three Working Groups:

- **WG1** - Role of risk assessment in policy development and decision making (Issue 1.5.1);
- **WG2** - Methodologies and tools for risk assessment and management applied to road operations (Issue 1.5.2);
- **WG3** - Management of emergency situations (Issue 1.5.3) and Risk and emergency management for combined and large hazards (Issue 1.5.4).

This report is an output of WG2, which deals with Issue 1.5.2. It is a product of a number of activities that have been undertaken by the members of WG2.

The terms of reference of the 2012-2015 Strategic Plan for WG2 are presented below:

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify and evaluate methodologies and tools for the management of natural and man-made risks in road operations and subsequent decision-making.</td>
<td>Further development of a toolbox as part of the Association’s web-based knowledge base for dissemination of basic risk management techniques in the road community.</td>
</tr>
<tr>
<td>Identify strategies applied to manage the risks associated with natural and man-made hazards including the adaptation of road infrastructure to climate change.</td>
<td>Case studies on techniques for managing the risks associated with natural and man-made hazards including the adaptation of road infrastructure to climate change.</td>
</tr>
</tbody>
</table>

Based on the terms of reference, WG2 has put a special emphasis on the methodologies and tools for risk assessment and management including a web-based risk management manual, and management of risks in relation to climate change. The structure of this report is shown below.

- **Chapter 1** Methodologies and tools for risk assessment and management
- **Chapter 2** Development of road disaster management system based on risk management techniques
- **Chapter 3** Managing risks in relation to climate change
- **Chapter 4** Web-based risk management manual
- **Chapter 5** Conclusions
- **Appendices**
Chapter 1 describes the methodologies and tools for risk assessment and management.

Chapter 2 presents a practical road disaster management system for various natural disasters by applying risk management techniques.

Chapter 3 provides an overview of the climate change and its effects on roads, and management of risks in relation to climate change.

Chapter 4 introduces a web-based risk management manual, which has been designed as an efficient tool for diffusing risk management techniques widely.

Chapter 5 summarizes the conclusions of the report.

1. METHODOLOGIES AND TOOLS FOR RISK ASSESSMENT AND MANAGEMENT

1.1. INTRODUCTION

There is global scientific consensus that the world’s climate is changing [IPCC, 2012] and the need for action is widely acknowledged. Despite existing uncertainties regarding the future climate, the White Paper Adapting to climate change: Towards a European framework for action [EU, 2009] states that ‘the challenge for policy-makers is to understand these climate change impacts and develop and implement policies to ensure an optimal level of adaptation’. In this context, adverse impacts are considered disasters when they produce widespread damage and cause severe alterations to the functioning of communities or societies. Chapter 3 of this report describes the effects of climate change for roads. Large parts of Siberia, Alaska and Canada consist of permafrost areas, where the ground is frozen all year round. But with climate change, this soil could at least partially defrost - with serious consequences for the environment, civilization and perhaps even the future climate. Possible consequences resulting from this as well as from the erosion of shores are also described in chapter 3.

However, the character and severity of impacts from climate extremes depend not only on the extremes themselves but also on risk exposure and vulnerability. Transport infrastructure plays a vital role in a country’s economy. Since extreme weather events are already happening on a larger scale and are predicted to get worse, it is essential for a country’s development to reduce the impact of climate change on the road network. In order to do so, decision makers and road operators need to understand first of all where the vulnerabilities on the transport systems are.

1.2. CLASSIFICATION OF RISK EVALUATION METHODOLOGIES

In most cases infrastructure is designed on the basis of guidelines and design standards that provide typical intensity data for climatic phenomena (wind speed, rainfall, snow depth, temperature variation etc.) associated with a defined return frequency (ten-year rainfall, hundred-year flood, etc.). The choice of return frequency expresses the risk level accepted by the public authorities with respect to financial costs deemed reasonable. Intensities (and frequencies) were defined correlative to the climate conditions experienced in the past and do not consider possible changes in the future due to climate change.
However, it should always be kept in mind that every kind of risk analysis - whatever method is finally used - is a more or less simplified model relying on preconditions and assumptions and can never totally reflect reality. Nevertheless, assessment models provide a much better understanding of risk-related processes than merely experience-based concepts can achieve.

In this chapter, a potential classification scheme for different risk evaluation methodologies will be introduced. To start with, risk managers need to specify the analytical level (strategic or operational) of the risk methodology to be used. In this context, strategic level implies the methodology to be adequate to come to solutions concerning the road network as a whole and hence to be primarily used in the middle to upper road management. Methodologies for strategic levels deal with questions concerning e.g. the availability of the road infrastructure for road users and transport facilities.

On the other side, risk evaluation methodologies on operational or project level (Project Management Methodology PRINCE2 in appendix 2) deal with specific questions such as tunnel safety, vulnerability of bridges due to strong winds and hurricanes etc. Risk methods need to be more sophisticated and rely on better and more detailed data.

Illustrations 1 and 2 give examples of risk matrices for man-made and natural disasters. With such classification scheme, different risk evaluation methodologies can be easily charted and used for decision-making processes.

In chapter 2 of this report, a practical procedure for the evaluation of risks resulting from natural disasters such as earthquakes and/or heavy rainfalls is proposed. In chapter 4 of this report, a web-based risk management manual is presented. This manual can be used to share ideas on risk management tools and also provides a central repository.

Illustration 1 - Classification of selected risk evaluation methods for man-made disasters
1.3. IDENTIFICATION OF RELEVANT HAZARDS

This chapter identifies potential hazards on road networks systems and on the natural environment, and the possible strategies state transportation agencies could adopt to respond or prepare for these impacts. The climate stressors examined in this chapter include changes in temperature, precipitation, sea-level rise, and hurricanes.

1.3.1. Change in extreme maximum temperature

The literature points to a likely increase in very hot days and heat waves. Heat extremes and heat waves will continue to become more intense, longer lasting, and more frequent in most states during this century. Increasing periods of extreme heat will place additional stress on infrastructure, reducing service life and increasing maintenance needs.

Impacts on road infrastructure

Extreme maximum temperature and prolonged-duration heat waves are expected to lead to premature deterioration of infrastructure. Temperature increases have the potential to affect and reduce the life of asphalt road pavements through softening and traffic-related rutting. Extreme heat can also stress the steel in bridges through thermal expansion and movement of bridge joints and paved surfaces.
1.3.2. Change in the range of maximum and minimum temperatures

Changes in the projected range of temperatures, including seasonal changes in average temperatures, can also affect road networks. The increased temperature ranges will likely benefit highways in some ways, while increasing risks in others.

**Impacts on road infrastructure**

The length of the season when it can snow will decrease, but winter precipitation is projected to rise. So there could be more snow during the shorter season, i.e., individual snowstorms could be bigger. Warmer winters will likely lead to less snow and ice on roadways than occurs today, but may possibly increase the incidence of slippery roads, while the incidence of frost heave and road damage caused by snow and ice is likely to decline. However, warmer winters may also lead to an increase in freeze-thaw conditions, creating frost heaves and potholes on road and bridge surfaces that increase maintenance costs. Pavements built on expansive clays, in particular, will see the subsurface expand or contract significantly given extended periods of wet weather or drought. Repairing such damage is already estimated to cost hundreds of millions of dollars in the United States annually [NCHRP, 2013].

The change in range of maximum and minimum temperatures will likely produce both positive and negative impacts on highway operations/maintenance. In many northern states, warmer winters will bring about reductions in snow and ice removal costs, lessen adverse environmental impacts from the use of salt and chemicals on roads and bridges, extend the construction season, and improve the mobility and safety of passenger and freight travel through reduced winter hazards.

On the other hand, with warmer winter temperatures, greater vehicle load restrictions may be required to minimize damage to roadways if they begin to subside and lose bearing capacity during the spring thaw period. With the expected earlier onset of seasonal warming, the period of springtime load restrictions might be reduced in some areas, but it is likely to expand in others with shorter winters but longer thaw seasons.

1.3.3. Changes in overall precipitation

Changes in precipitation - both rain and snow - are going to vary widely across various regions. These changes are expected to affect road networks in several ways, depending on specific regional precipitation levels and geographic conditions.

**Impacts on road infrastructure**

In areas with increased precipitation, there is greater risk of short- and long-term flooding (e.g. more spring floods). In other areas, more precipitation may fall as rain rather than snow in winter and spring, increasing the risk of landslides, slope failures, and floods from the runoff, which can cause road washouts and closures. In addition, northern areas are projected to have wetter winters, exacerbating spring river flooding. In other areas, the increase in precipitation could lead to higher soil moisture levels affecting the structural integrity of roads, bridges, and tunnels and leading to accelerated deterioration. If soil moisture levels become too high, the structural integrity of roads, bridges, and tunnels, which in some cases are already under age-related stress
and in need of repair, could be compromised. Standing water can also have adverse impacts on the road base. Overall, the increased risk of landslides, slope failures, and floods from runoff will likely lead to greater road repair and reconstruction needs.

1.3.4. Increased intense precipitation

Heavier rainfall downpours and more intense storms are very likely to become more frequent e.g. in widespread areas of the United States and Europe. This intense precipitation has immediate effects on highway operations and over the long term could change ecological systems that ultimately influence highway design and operations/maintenance.

**Impacts on road infrastructure**

In areas with heavy winter rain, mudslides and rockslides (case study in appendix 1) can damage roads from washouts and undercutting and lead to permanent road closures. Heavy precipitation and increased runoff during winter months are likely to increase the potential of flooding to tunnels, culverts, and coastal highways. In the future, the combination of a generally drier climate which will increase the chance of drought and wildfires) and more frequent extreme downpours (and occasionally wet winters) is likely to cause more mud- and landslides that can disrupt major roadways. An Australian study found that in Victoria the projected increase in the frequency and intensity of extreme rainfall events has the potential to cause significant flood damage to roads - especially tunnel infrastructure - due to acceleration in the degradation of materials, increased ground movement, changes in groundwater affecting the chemical structure of foundations, and fatigue of structures from extreme storm events. Bridges are more prone to extreme wind events and scouring from higher stream runoff, and bridges, signs, overhead cables, and tall structures face increased risk from greater wind speeds.

1.3.5. Sea-level rise

Sea levels will continue to rise as a result of thermal expansion and the possible loss of mass from ice sheets.

**Impacts on road infrastructure**

Infrastructure in coastal areas is expected to be heavily affected by rising sea levels, often compounded by regional subsidence (the sinking of a land mass due to compaction of sediments or tectonic forces). Coastal roads are at risk from the combination of rising sea levels along with a heightened coastal flooding potential from tropical and non-tropical storms. An estimated 60,000 miles of coastal highway in the United States are already exposed to periodic flooding from coastal storms and high waves [NCHRP, 2013]. Along with the temporary and permanent flooding of roads and tunnels, rising sea levels and storm surges will likely cause erosion of coastal road bases and bridge supports. In addition to more frequent and severe flooding, underground tunnels and other low-lying infrastructure may also experience encroachment of saltwater, which can lead to accelerated degradation of infrastructure. This can reduce the structure’s life expectancy, increase maintenance costs as well as the potential for structural failure during extreme events.
Underground tunnels and other low-lying infrastructure will experience more frequent and severe flooding. Higher sea levels and storm surges may also erode the road base and undermine bridge supports. The loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action.

1.3.6. Greater hurricane intensity

The intensity of the most powerful hurricanes is projected to increase, with larger peak wind speeds and more intense precipitation. The number of category 4 and 5 hurricanes is projected to increase, while the number of less powerful hurricanes is projected to decrease. Three aspects of hurricanes are relevant to transportation: precipitation, winds, and wind-induced storm surge. Stronger hurricanes have longer periods of intense precipitation, higher wind speeds (damage increases exponentially with wind speed), and higher storm surge and waves. Increased intensity of strong hurricanes could lead to more evacuations, infrastructure damage and failure, and interruptions in transportation service. The prospect of an increasing number of higher category hurricanes has serious implications for the highway system.

Impacts on road infrastructure

Roads are likely to face increased flooding in the aftermath of strong hurricanes. Prolonged inundation can lead to long-term weakening of roadways. As a result of Hurricane Katrina, some pavements showed that they suffered a permanent strength loss equivalent to 2 inches of pavement (Gaspard et al. 2007). Roads and bridges can be damaged during hurricanes by wave battering (from water driven inland by storm surge) and high winds. Concrete bridge decks weighing many tons can literally be blown or floated off their supports during hurricanes, as seen during Hurricanes Katrina and Rita. The widespread damage to highways from these hurricanes illustrated the powerful effects of these intense tropical storms. Damage to signs, lighting fixtures, and supports are also products of hurricane force winds.

1.4. ROAD MANAGEMENT ACTIVITIES

As can be seen from table 1, road managers have to deal with a wide variation of management activities, ranging from decision-making and prioritization of national transport infrastructure plans to detailed maintenance procedures.

Risk assessment methodologies can be distinguished in two methods to assess or verify the risk of road infrastructure. Both of them have strengths and limitations and it depends on the specific situation on hand which to use.
<table>
<thead>
<tr>
<th>Road management activity</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision making and prioritization</td>
<td>• Travel demand matrix&lt;br&gt;• Overall network planning&lt;br&gt;• National transport infrastructure plans&lt;br&gt;• Accessibility of major centres&lt;br&gt;• Etc.</td>
</tr>
<tr>
<td>Project selection and planning</td>
<td>• Routing&lt;br&gt;• Alignment&lt;br&gt;• Cost-benefit analysis&lt;br&gt;• Etc.</td>
</tr>
<tr>
<td>Road design</td>
<td>• Intersection layout&lt;br&gt;• Environmental aspects&lt;br&gt;• Traffic safety&lt;br&gt;• Etc.</td>
</tr>
<tr>
<td>Construction and heavy maintenance</td>
<td>• Refurbishment&lt;br&gt;• Structural maintenance&lt;br&gt;• Etc.</td>
</tr>
<tr>
<td>Operations</td>
<td>• Level of service&lt;br&gt;• Operational traffic management&lt;br&gt;• Operational availability of road infrastructure&lt;br&gt;• Etc.</td>
</tr>
<tr>
<td>Maintenance</td>
<td>• Operational maintenance&lt;br&gt;• Winter services (snow removal, defrosting etc.)&lt;br&gt;• Exchange of damaged guardrails after accidents&lt;br&gt;• Etc.</td>
</tr>
<tr>
<td>Crisis management and emergency planning</td>
<td>Reactive approach</td>
</tr>
</tbody>
</table>

1.4.1. Reactive approach

This approach is carried out by searching for solutions to problems revealed by previous major catastrophes or natural hazards and are aimed at avoiding their reoccurrence. Classical methods of root cause analysis fall into this approach. This method has the advantage of easily sensitizing high-level administrators who will be willing to provide the necessary resources to prevent them.

Their main limitation is given by the fact that only well documented accidents can be analysed and these are usually the most important, catastrophic-type of events. Many other events that have occurred but were not adequately reported cannot be rigorously analysed and lessons cannot be drawn and used.

1.4.2. Proactive approach

The proactive approach is based on a search for all potential failures and errors, estimating their risk and prioritizing efforts to avoid accidental exposure from those events leading to higher risk. The approach provides a kind of made-to-measure assessment for each particular facility. The main limitations of the method is that, in general, it is highly time-consuming and requires the involvement of a multidisciplinary group of specialists, being for this reason costly and likely to be unaffordable for small organisations with limited human and material resources.
2. DEVELOPMENT OF ROAD DISASTER MANAGEMENT SYSTEM BASED ON RISK MANAGEMENT TECHNIQUES

2.1. INTRODUCTION

Risk management techniques are well worth applying to the disaster management of infrastructures. A uniform quantitative evaluation of risks of various infrastructures for various disasters will be of particular interest in prioritizing disaster prevention measures. There are cases where risk management techniques are applied to road disaster management. In New Zealand for instance, there is an established set of risk management procedures called the Risk Management Process Manual (Transit New Zealand, 2004), which is applied to their road management practice. This manual was published by the Transit New Zealand (currently, New Zealand Transport Agency) that is responsible for the stewardship of New Zealand’s state highways, and has the following features:

1. both threat and opportunity are considered as risks. Threat is defined as an event that has the potential to move the outcome of an activity to a more unfavourable position. Opportunity is defined as an event that has the potential to move the outcome of an activity to a more favourable position;
2. a risk is measured in terms of a combination of the likelihood of an event and its consequences, where the likelihood of an event and its consequences are rated to allow quantitative evaluation of risks for various road facilities against various disasters.

In the present study (Tamura, 2013) we applied the concept of this manual to proposing a practical method to systematically evaluate the risk of road facilities caused by natural disasters. Road facilities included in our study were bridges, embankments, tunnels and slopes. Earthquakes, tsunamis and heavy rainfalls were the major natural disasters considered. Regarding damage to road facilities, direct damage and indirect damage were both assumed. Particularly, emphasis was put on evaluating risks of damage to various road facilities due to various disasters by using a common index. In examining the priority of road disaster prevention measures, we incorporated into the analysis the concept of opportunity, which is a favourable outcome incidentally resulting from road disaster prevention measures.

As mentioned previously, the primary objective of this study is to present a comprehensive and practical method for evaluating risks to different road facilities caused by different disasters. In this process, it is necessary to estimate various factors such as the likelihood of hazards, damage level of each road facility and restoration cost, and then rate them in a uniform manner. Those factors were estimated in a simple and practical manner by using available information. Further study will be necessary to improve the accuracy of estimating each factor, and note that it is out of the scope of the present study.

Finally, we performed a case study on the proposed method for roughly 110 km section of a national highway spanning along the Pacific coastline of Japan. On this target section of the highway, there were a variety of road facilities. Seismicity of the region is high, and disasters caused by heavy rainfalls such as typhoons have also occurred. In the case study we systematically evaluated the risk of damage to the highway, and based on the evaluation results we examined the priority for road disaster prevention measures, where threats and opportunities were considered.
2.2. EVALUATION PROCEDURE FOR ROAD DISASTER RISKS

2.2.1. Overview

We propose a practical procedure for evaluating road disaster risks caused by natural disasters such as earthquakes and heavy rainfalls that frequently occur in Japan. The proposed evaluation procedure can be applied when examining the priority for road disaster prevention measures and is outlined as follows:

1. Identify natural disasters (hazards) that may affect the target area and roads. Then, determine if the damage actually occurs or not and the damage level by combining the vulnerability of each road facility and hazard. Evaluate the direct damage such as human damage and physical damage to each road facility, and the indirect damage such as disruption of road traffic. (Risk identification);

2. Formulate a table to rate the consequences of damage for quantification and to evaluate the impact of each damaged facility. Likewise, rate the likelihood of hazard. Then, evaluate the risk to road facility due to hazard by multiplying the likelihood of hazard and its consequences (International Organization for Standardization and International Electrotechnical Commission, 2002). (Risk analysis and evaluation);

3. Develop a menu of disaster prevention measures for road facilities that are found to require measures, and examine the priority for road disaster prevention measures, in which opportunities, which are favourable outcomes incidentally resulting from measures against threats, are considered. (Risk treatment).

Illustration 3 shows the proposed procedure for road disaster risk management, and each process is described below.

<table>
<thead>
<tr>
<th>Identification of natural disasters (hazards)</th>
<th>Evaluation of damage to road facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Evaluation of direct damage</td>
</tr>
<tr>
<td></td>
<td>Evaluation of indirect damage</td>
</tr>
<tr>
<td></td>
<td>Evaluation of consequences</td>
</tr>
<tr>
<td>Evaluation of hazard likelihood</td>
<td>Evaluation of risks</td>
</tr>
<tr>
<td>Examination of disaster prevention measures</td>
<td></td>
</tr>
</tbody>
</table>
2.2.2. Identification of natural disasters (hazards)

Hazards to be considered include earthquakes, tsunamis, overtopping waves and slope disasters caused by earthquake or heavy rainfall. Effects of hazards are simplified for them to be easily used in the evaluation of damage to road facilities described in the next section. For instance, the effects of earthquakes are modelled by seismic intensity, and those of tsunamis are represented by inundation depth.

2.2.3. Evaluation of damage to road facilities

For the road facilities, such as bridges, embankments, tunnels and slopes, on the target section of road, determine whether damage is brought by the hazards identified above to each of those facilities, and evaluate the damage level. We refer to previous research results to establish the methods for evaluating damage to individual road facilities caused by various hazards.

2.2.4. Evaluation of direct damage

Direct damage refers to human damage or damage to road users and the restoration cost of road facilities, which represent physical damage to road facilities. Human damage covers damage that may cause fatalities, while restoration cost is estimated costs for both temporary repair work and permanent restoration work of the damaged facilities.

2.2.5. Evaluation of indirect damage

For indirect damage, we evaluated the loss due to traffic detour. The period of indirect damage refers to the period from the occurrence of the disaster to the time when the road is reopened to the general traffic after temporary restoration work.

2.2.6. Evaluation of consequences

In this process, we evaluated the consequences of each combination of road facility and disastrous event, assuming that the disastrous event occurs. The likelihood of disastrous event shall be evaluated in the next process, and the level of damage to road facilities varies depending on their vulnerability even if the same level of hazard occurs.

We employed a rating technique to evaluate the consequences of disastrous events, which categorizes the impact level based on an impact evaluation standard chart. In our study, the impact level for each of the three kinds of damage, i.e., human damage, restoration cost, and economic loss (the first two are direct damage and the third is indirect damage) is categorized into four classes: major, medium, minor, and none. We rated each class as 10, 5, 1, and 0, respectively, and evaluated the magnitude of the consequence by the total of those scores. Table 2 shows the rating of consequences as the basis for evaluating the impact level in this study. The threshold levels were set for each type of damage so that equivalent impact levels were assumed among the different types of damage. We surveyed the opinions of road administrators responsible for road management when we established the scores and threshold levels in Table 2. There was some degree of arbitrariness in determining them, thus there should be room for reviewing and modifying them in future trials. Still, this technique enabled us to consistently evaluate the risks to diverse road facilities resulting from different hazards.
### TABLE 2 - RATING OF CONSEQUENCES

<table>
<thead>
<tr>
<th>Risk</th>
<th>Influence</th>
<th>Rating</th>
<th>Human damage (Fatalities)</th>
<th>Restoration cost</th>
<th>Economic loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threat</td>
<td>Major</td>
<td>10</td>
<td>≥1</td>
<td>≥150M yen</td>
<td>≥150M yen</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>5</td>
<td>&lt;1</td>
<td>50M to 150M yen</td>
<td>50M to 150M yen</td>
</tr>
<tr>
<td></td>
<td>Minor</td>
<td>1</td>
<td>&lt;50M yen</td>
<td>&lt;50M yen</td>
<td>&lt;50M yen</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Opportunity</td>
<td>Minor</td>
<td>1</td>
<td>&lt;50M yen</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>5</td>
<td>&lt;1</td>
<td>50M to 150M yen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Major</td>
<td>10</td>
<td>≥1</td>
<td>≥150M yen</td>
<td></td>
</tr>
</tbody>
</table>

### 2.2.7. Evaluation of hazard likelihood

We employed an annual probability of occurrence for each hazard to measure its likelihood. Although large-scale and infrequent hazards such as earthquakes and tsunamis may have non-stationarity, we assumed stationary processes for simplicity. Hazard likelihood was scored on a scale of 10, 5, and 1 corresponding to the level of annual occurrence likelihood as likely, medium, and rare, as shown in Table 3. Similar to the above evaluation of consequences, we surveyed the opinions of road administrators when we introduced the rating criteria for the hazard likelihood. The scores and threshold levels in Table 3 are somewhat arbitrary, but they are helpful in evaluating the likelihood of various hazards in a uniform manner. There is also room for reviewing and modifying Table 3 in future trials.

### TABLE 3 - RATING OF LIKELIHOOD OF HAZARD

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Annual probability of occurrence</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likely</td>
<td>≥50%</td>
<td>10</td>
</tr>
<tr>
<td>Medium</td>
<td>10 to 50%</td>
<td>5</td>
</tr>
<tr>
<td>Rare</td>
<td>≤10%</td>
<td>1</td>
</tr>
</tbody>
</table>

### 2.2.8. Evaluation of risks

We evaluated the risk quantitatively by multiplying the likelihood of hazard and its consequences. Both the likelihood of hazard and its consequences were scored as mentioned in sections 2.2.6. and 2.2.7.

### 2.2.9. Examination of disaster prevention measures

We considered both structural and non-structural measures for the risks that were revealed to need treatment. The priority of measures was then examined based on the cost of disaster prevention measures and the effectiveness of the measures. Evaluation of risks after implementation of measures was made in terms of both threat and opportunity. Applying the concept of opportunity presented in the Risk Management Process Manual of Transit New Zealand, we evaluated the favourable outcomes incidentally achieved from the implementation of road disaster prevention measures as opportunities.
2.3. CASE STUDY ON ROAD DISASTER RISK MANAGEMENT

2.3.1. Target area and route

We performed a case study on roughly 110 km section of a national highway running through the Pacific coast area of Japan. Along this section of the highway, natural disasters expected to occur include earthquakes, tsunamis, and heavy rainfalls. Table 4 summarizes the numbers of road facilities on the target section.

<table>
<thead>
<tr>
<th>TABLE 4 - NUMBER OF ROAD FACILITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road facility</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Bridge</td>
</tr>
<tr>
<td>Embankment</td>
</tr>
<tr>
<td>Slope</td>
</tr>
<tr>
<td>Tunnel</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

2.3.2. Evaluation of damage to road facilities

a) Direct and indirect damage and damage level

Table 5 shows the combination of hazards and road facilities to be used for damage evaluation. Table 6 lists direct damage and indirect damage studied. In this study, we evaluated damage with a focus on human damage at each road facility in case a hazardous event occurs. Such damage is classified into three categories: damage that may cause fatalities (Damage Level I), damage that may cause injuries (Damage Level II), and damage causing no human damage. In principle, we conducted risk evaluation for the kind of damage involving fatalities. Detailed conditions that dictate damage evaluation are as follows:

<table>
<thead>
<tr>
<th>TABLE 5 - COMBINATION OF HAZARDS AND ROAD FACILITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Earthquake</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tsunami</td>
</tr>
<tr>
<td>Heavy Rainfall</td>
</tr>
<tr>
<td>Overtopping wave</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 6 - CLASSIFICATION OF DAMAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Direct damage</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Indirect damage</td>
</tr>
</tbody>
</table>
1. both direct damage (human damage and restoration cost) and indirect damage (loss due to traffic detour) are evaluated when Damage Level I occurs, in principle. Refer to the grey areas in table 7;
2. neither direct damage nor indirect damage is evaluated in case of damage that does not cause fatalities;
3. no fatalities have been reported due to collapse of road embankments or tunnels at least in the recent earthquakes, thus we excluded the earthquake-embankment and earthquake-tunnel combinations from risk evaluation;
4. note that no human damage is assumed to occur from a slope disaster caused by heavy rainfall on the road section with precautionary road closure; however, if damage of a scale that may cause fatalities occurs, the restoration cost and indirect damage are evaluated. This case is highlighted in blue in table 7;
5. for overtopping waves, it is assumed that no human damage occurs because traffic control is applicable in advance. Since it is difficult to assume blocking materials and their amount caused by overtopping waves, no restoration cost is evaluated either. Notwithstanding the foregoing, indirect damage inflicted by stones brought over the road surface or road blockage by such stones is estimated, which is marked in blue in table 7.

### TABLE 7 - PATTERN OF DAMAGE OCCURRENCE

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Damage level</th>
<th>Direct damage</th>
<th>Indirect damage</th>
<th>Risk evaluation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Human</td>
<td>Restoration</td>
<td>Economic</td>
<td></td>
</tr>
<tr>
<td>Occurred</td>
<td>Damage may cause fatalities (Damage Level I)</td>
<td>Damage</td>
<td>No damage</td>
<td>Damage</td>
<td>Applicable</td>
</tr>
<tr>
<td></td>
<td>Damage may cause injuries (Damage Level II)</td>
<td>Damage</td>
<td>Damage</td>
<td>Damage</td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td>No human damage</td>
<td>No damage</td>
<td>Minor damage or no damage</td>
<td>Damage</td>
<td>Applicable</td>
</tr>
<tr>
<td>Did not occur</td>
<td>No damage</td>
<td>No damage</td>
<td>No damage</td>
<td>Damage</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

b) Evaluation of damage to bridges by earthquake or tsunami

Physical damage to a bridge by an earthquake equivalent to Damage Level I refers, in principle, to a fall of a superstructure. The procedure adopted for evaluating bridge damage level in this study is the one proposed by Kobayashi and Unjoh (2005). We regard Damage Level A according to their definition as Damage Level I.

The level of bridge damage by a tsunami was evaluated by a procedure proposed by the National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism (2008). The washing away of a superstructure by tsunami corresponds to Damage Level I.
c) Evaluation of damage to slope by earthquake or heavy rainfall

A slope disaster that results in Damage Level I occurs when a vehicle on the road is buried under soils. When the collapsed soils by earthquake or heavy rainfall are estimated to reach a height greater than the height of a vehicle window (1 m) at the centre of a roadway, the damage level is judged as Damage Level I. In this process, it was assumed that surface soils on a slope collapse with a uniform depth, and the collapsed soils deposit in a triangular shape from the road edge on the slope side, as schematically illustrated in illustration 4. A collapse depth on the slope was assumed to be 1 m in the case study after a geotechnical field survey of the site.

The procedure for evaluating slope damage caused by earthquake consists of evaluations of the likelihood of slope collapse studied by the Miyagi Prefectural Government (1997) and the effects of slope failure on vehicles. In evaluating slope damage due to heavy rainfall, the results of the comprehensive road disaster management inspection by the Ministry of Land, Infrastructure, Transport and Tourism were applied. It was assumed that the slopes judged to require preventive measures according to the inspection but not yet measured collapse when continuous or hourly rainfall exceeds a threshold level.

\[
\text{Collapse depth } d(=1m) \\
\text{Collapse volume } V_1 \\
\text{Loosened volume } V_2 = 1.3 \times V_1 \\
\text{Height at roadway center } h_c \\
\text{Slope angle } \Theta = 30^\circ \\
\text{Road width}
\]

Illustration 4 - Deposit of collapsed soils on road surface

d) Road facilities evaluated to suffer damage

As a result of the above damage evaluation, 22 cases of a combination of hazards and road facilities were identified as, in principle, they would induce damage with Damage Level I, and were qualified as subjects for risk evaluation, as shown in table 8. Note that two slopes were judged to suffer damage with Damage Level I from both earthquake and heavy rainfall. Thus, 20 were identified as damaged road facilities.
### TABLE 8 - NUMBER OF DAMAGED ROAD FACILITIES

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Road facility</th>
<th>Damaged facility</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Earthquake</strong></td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Embankment</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Tunnel</td>
<td>-</td>
</tr>
<tr>
<td><strong>Tsunami</strong></td>
<td>Bridge</td>
<td>1</td>
</tr>
<tr>
<td><strong>Heavy Rainfall</strong></td>
<td>Slope</td>
<td>5</td>
</tr>
<tr>
<td><strong>Overtopping wave</strong></td>
<td>Road</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>

2.3.3. Risk evaluation

**a) Evaluation of likelihood of hazard**

The likelihood of earthquakes and ensuing tsunami was evaluated from the mean recurrence period of plate boundary earthquakes. Note that the target section in the highway runs through the Pacific coast of Japan, and the most significant earthquake over the target section is one that occurs at a plate boundary off the Pacific coast.

A precautionary road closure section was designated within the target highway, and we assumed that slope disasters might occur at the precautionary road closure section and the rest of target highway when continuous or hourly rainfall exceeds the threshold level set for road closure. For the whole target highway section, the likelihood of heavy rainfall was evaluated from the annual average number of rainfalls exceeding the threshold level of either continuous or hourly rainfall established for road closure.

The likelihood of overtopping waves was computed from the annual average number of road closures exceeding 12 hours due to overtopping waves.

**b) Evaluation of direct damage**

The number of fatalities was evaluated from the average number of passengers for each type of vehicle and the expected number of vehicles on the road section or facility that was evaluated to suffer Level I damage. The latter was further inferred from the average traffic volume and travel velocity based on the road traffic census.

The restoration cost of a bridge damaged by a tsunami includes both temporary and permanent repair costs. The former was estimated as the cost of installing a temporary bridge. The latter was estimated as the cost for replacing a bridge deck and bearings. These cost estimations are rough estimations, because restoration cost is simply classified into three categories and rated as indicated in table 2 in our proposed procedure, and detailed cost estimation is beyond the scope of the present study.

The restoration cost of damaged road slope by earthquake or heavy rainfall is also composed of temporary and permanent restoration costs. Temporary restoration cost was estimated as the cost of removal of collapsed soils and installation of slope protection nets. The rough estimate cost of disaster prevention measures proposed in the comprehensive road disaster management inspection was adopted as the permanent restoration cost.
c) Evaluation of indirect damage

For indirect damage, loss due to traffic detour was estimated according to the calculation of traveling cost before and after roadwork as specified in the Cost-Benefit Analysis Manual by the Ministry of Land, Infrastructure, Transport and Tourism (2003). To be specific, the traveling cost in ordinary time and in case one takes a detour instead of taking the damaged road section in the event of a disaster were calculated. The difference between the two costs was regarded as the loss resulting from traffic detour. For this calculation of traveling cost, both the time cost, which represents the traveling time converted into the monetary value, and driving cost, which represents all the cost related to traveling of a vehicle except the time cost, were included. It was also assumed that no change in traffic demand would occur between ordinary time and disaster time. The time cost and driving cost were calculated by using the type-specific traffic volume in the road traffic census, time-value basic unit and traveling cost basic unit in the Cost-Benefit Analysis Manual.

d) Risk register table and risk curve

We performed risk evaluation on the 20 road facilities identified by the damage evaluation process in section 2.3.2. As an opportunity, we introduced a case in which slope disaster damage to houses standing along the opposite side of the road is prevented by slope measures. With this opportunity, it is possible to avert the occurrence of human damage and restoration cost, i.e., cost for sediment removal and house repair. Site No.19 is the slope where the opportunity emerges.

Table 9 shows a risk register table. A risk is calculated here as the product of the likelihood of disaster and the magnitude of its consequences. Illustration 5 shows a risk curve, which plots the likelihood of disaster to its vertical axis and the magnitude of its consequences to the horizontal axis. On this diagram, a risk located in the top right region is one greater than others outside that region.

For the damage to slopes by earthquakes, although the annual likelihood of the event is small, the risk is evaluated high at sites where the human damage and/or the economic loss due to the lack of detour route is large (Site Nos.3, 5-7, 9, and 17-19).

Concerning the damage to slopes by heavy rainfall, no human damage occurs at the slopes within a precautionary road closure section (Site Nos.10-12), while the annual occurrence of heavy rainfall is judged to be likely because of the local rainfall characteristics at those sites. Eventually, the risks at those slopes occupy the top three in the 22 cases analysed. Human damage may occur at slopes outside a precautionary road closure section (Site Nos.13 and 14), and the magnitudes of consequences at those sites become rather large. However, since the likelihood of heavy rainfall occurring there annually is medium, the risks at these slopes are rated after those at the slopes within a precautionary road closure section.
<table>
<thead>
<tr>
<th>No.</th>
<th>Hazard</th>
<th>Facility</th>
<th>Length (km)</th>
<th>Hazard rating</th>
<th>Threat</th>
<th>Opportunity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Human</td>
<td>Restoration</td>
</tr>
<tr>
<td>1</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Overtopping wave</td>
<td>Road</td>
<td>8.9</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.4</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10*</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.1</td>
<td>10</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11*</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.3</td>
<td>10</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>12*</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.3</td>
<td>10</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.3</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>Overtopping wave</td>
<td>Road</td>
<td>1.4</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>Overtopping wave</td>
<td>Road</td>
<td>1.1</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.6</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.3</td>
<td>1</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.3</td>
<td>1</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>Tsunami</td>
<td>Bridge</td>
<td>0.03</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

* Within precautionary road closure section.
Site No.20 is a bridge where tsunami is expected. The affected length of the road facility or bridge length is shorter than those of damaged slopes, and the resultant human damage and restoration cost are rated small. In addition, as the likelihood of a tsunami occurring annually is rare, the risk at this site turns out to be small.

For damage to roads due to overtopping waves (Site Nos.2, 15 and 16), although likelihood of the event is large, the risk at those sites is evaluated to be small. This is because no human damage is judged to occur as traffic control is feasible in advance. In addition, the economic loss there is small as the length of time with traffic blockage is set relatively short.

Among the road facilities with large risks, the five slopes damaged by heavy rainfall (Site Nos.10-14) are in the top positions and the eight earthquake-damaged slopes (Site Nos.3, 5-7, 9, and 17-19) follow the former. As explained above, plotting the risks for combinations of different hazards and different road facilities on the same risk curve can evaluate the magnitude of risk in a quantitative and integrated manner. One of the features of the risk evaluation conducted in the present study is that the evaluation results are generally more affected by the likelihood of event than by its consequences.

### 2.3.4. Examination of road disaster prevention measures

Here, we introduce the idea that prevention of damage by implementing a road disaster prevention measure is the effect of that measure; define the ratio of the measure’s effect to its cost as the index of cost-effectiveness; and examine the priority of road disaster prevention measures. Note that we do not consider the residual risk for simplicity reasons, and assume that disaster prevention measures remove disastrous risks from the road facilities.

The preventive measure cost of a bridge for tsunami was estimated as the cost of installing unseating prevention structures in transverse direction. We employed the rough estimate cost of disaster prevention measures proposed in the comprehensive road disaster management inspection as the measure cost of slopes for earthquake or heavy rainfall. At road facilities where opportunity exists, such as Site No.19, we included both the elimination of threat and the effects of opportunity in the the benefits of road disaster prevention measures.

Slope protection work is effective for the two types of hazards, i.e., earthquake and heavy rainfall, and the implementation of slope protection work prevents disasters by earthquake and heavy
rainfall simultaneously. Thus, for the slopes where the damage levels by both hazards are rated as Damage Level I (Site Nos.10 and 13), the risks from those two hazards are put together to calculate the measure effects. Within a precautionary road closure section, the basic idea is that human damage resulting from slope damage by heavy rainfall can be prevented. However, since implementing slope protection work will mitigate restoration cost and indirect damage due to heavy rainfall, and is simultaneously capable of reducing earthquake damage, we decided to evaluate the measure effects for those slopes (Site Nos.10-12). Finally, concerning the sites affected by overtopping waves (Site Nos.2, 15 and 16), traffic control or on-going non-structural measures seem to be sufficient. Therefore, those sites are excluded from the list of sites that will be examined for prioritizing road disaster prevention measures.

*Table 10* shows a risk treatment plan arranged in descending order of cost-effectiveness. Note that cost-effectiveness is measured by a common index for various road facilities exposed to various natural disasters as shown in *table 10*, and this table can be applied to prioritizing road disaster measures.

**TABLE 10 - RISK TREATMENT PLAN**

<table>
<thead>
<tr>
<th>No.</th>
<th>Hazard</th>
<th>Facility</th>
<th>Length (km)</th>
<th>Hazard-rating</th>
<th>Consequence</th>
<th>Reduced risk (B) (1,000 yen)</th>
<th>Cost (C)</th>
<th>B/C*</th>
<th>Order</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.3</td>
<td>1</td>
<td>35</td>
<td>35</td>
<td>1,000</td>
<td>3,500</td>
<td>1</td>
<td>Opportunity</td>
</tr>
<tr>
<td>12</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.3</td>
<td>10</td>
<td>15</td>
<td>150</td>
<td>9,000</td>
<td>1,667</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.3</td>
<td>10</td>
<td>15</td>
<td>150</td>
<td>10,000</td>
<td>1,500</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.1</td>
<td>1</td>
<td>16</td>
<td>16</td>
<td>16,000</td>
<td>788</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>1.0</td>
<td>11</td>
<td>11</td>
<td>110</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Tsunami</td>
<td>Bridge</td>
<td>0.03</td>
<td>1</td>
<td>16</td>
<td>16</td>
<td>3,600</td>
<td>444</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>16</td>
<td>16</td>
<td>4,000</td>
<td>400</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.1</td>
<td>1</td>
<td>11</td>
<td>11</td>
<td>3,000</td>
<td>367</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.5</td>
<td>1</td>
<td>20</td>
<td>20</td>
<td>7,000</td>
<td>286</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.3</td>
<td>1</td>
<td>11</td>
<td>11</td>
<td>29,000</td>
<td>228</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Heavy rainfall</td>
<td>Slope</td>
<td>0.1</td>
<td>5</td>
<td>7</td>
<td>35</td>
<td>19,000</td>
<td>184</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>16</td>
<td>16</td>
<td>10,000</td>
<td>160</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.4</td>
<td>1</td>
<td>20</td>
<td>20</td>
<td>13,000</td>
<td>154</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.6</td>
<td>1</td>
<td>30</td>
<td>30</td>
<td>25,000</td>
<td>120</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>20</td>
<td>20</td>
<td>23,000</td>
<td>87</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.3</td>
<td>1</td>
<td>25</td>
<td>25</td>
<td>32,000</td>
<td>78</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>20</td>
<td>20</td>
<td>28,000</td>
<td>71</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Earthquake</td>
<td>Slope</td>
<td>0.2</td>
<td>1</td>
<td>20</td>
<td>20</td>
<td>40,000</td>
<td>50</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

* B/C = B × 10^5/C
The measure costs are essentially different from the restoration costs, and it would be ideal if different ratings for the measure and restoration were developed. However, we do not have enough experience in developing different ratings for these two costs, thus we attempted to apply the rating for restoration costs, which is shown in Table 2, to the measure costs. In this case, measure cost at any site is classified as minor, and this makes the ranking of cost-effectiveness the same as that of risk. Thus, we adopted the amount of money for estimating the measure cost in Table 10.

The effect of road disaster prevention measures at Site No.19 increased from 20 to 35 by including the opportunity, compared with the case where threat alone was considered. At this site, the implementation of slope protection work was effective in preventing damage to houses standing along the opposite side of the road, and this effect was regarded as an opportunity. However, as shown in Table 10, the cost-effectiveness of the road disaster prevention measures for Site No. 19 seems to be highly evaluated because of the small measure cost rather than the impact of the opportunity. Similarly, a high score is given to the cost-effectiveness at Site No.20, where the tsunami is expected to cause damage to the bridge, because of the small measure cost.

At Site Nos.10 and 13, which are slopes where damage is expected from two hazards, i.e., earthquake and heavy rainfall, the road disaster prevention measures have larger effect by considering the prevention of the two hazards rather than the prevention of either single hazard. At the three slopes damaged by heavy rainfall (Site Nos.10-12) including the above Site No.10, although the measure cost is relatively high, the risk is rated large, which eventually leads to the higher evaluation of the cost-effectiveness of the road disaster prevention measures.

2.4. CONCLUDING REMARKS

We proposed a practical system to systematically evaluate damage risks to road facilities by natural disasters and conducted a case study on a section of the national highway. The proposed procedure particularly focuses on the quantitative evaluation of risks to various road facilities from various disasters by using a common index, and incorporates both threats and opportunities into the analysis. Opportunities are favourable outcomes incidentally resulting from the implementation of road disaster prevention measures. Based on the idea that prevention of damage by implementing a road disaster prevention measure is the effect of the measure, we examined the priority of measures from the viewpoint of the ratio of the measure effects to its cost.

Although further detailed study will be necessary to improve the rating of the likelihood of hazards and their consequences, which has been introduced to make the quantitative evaluation of risks in our study, the proposed procedure is helpful in prioritizing road disaster prevention measures by comparing the impacts of various disasters on various road facilities.
3. MANAGING RISKS IN RELATION TO CLIMATE CHANGE

3.1. INTRODUCTION

Since the origins of mankind, until 1850, world population was below 1 billion inhabitants, nevertheless, in only 150 years, with Industrial Revolution and medical progress, population has grown 6 times its size and reached 7 billion inhabitants by 2012.

There is a correlation between population and machinery usage, unfortunately both are increasing quite fast, producing great amounts of \( \text{CO}_2 \). Illustration 6 shows the \( \text{CO}_2 \) concentrations in the last 1,000 years.

Illustration 6 - \( \text{CO}_2 \) concentrations in the last 1,000 years

It is estimated that in the year 2010, that the total number of vehicles in the world were beyond 1 billion, which means that there is practically 1 vehicle per 7 habitants in the world. As a result, the increase in the atmosphere’s carbon dioxide in the last 150 years is approximately 36%.

In the 20th century, average temperature worldwide increased in more than half a degree. In the industrialized countries where greenhouse effect gases due to fossil fuel burning is bigger, temperature is increasing faster, reaching a 1°C difference. Illustration 7 shows the sea surface temperature.

Illustration 7 - Sea surface temperature
Unpredictable power of Atlantic storms hitting coasts leaves destruction as they go by. Wind destroys facilities and water washes away everything in its path, besides several landslides leaving countless damage to highway infrastructure. Now that the mechanism has gone off, temperate climate is decreasing gradually, apart from the blistering heat; a consequence of global warming is rain violence in our regions.

Climate mismatch is bigger each time and its consequences more dramatic, today flooding is a permanent threat in the whole world.

### 3.2. CLIMATE CHANGE

The origin of climate change has a scientific explanation:

- earth absorbs solar radiation as part of its natural warming process;
- part of this radiation is reflected to space by oceans, lakes and ice in the Poles;
- before leaving to space, part of the radiation is absorbed by clouds and greenhouse gases effect in the atmosphere and reflected back towards earth. This represents more steam accumulation in the atmosphere, which is causing more rain in the planet;
- the problem emerges in this phase, because in the last 150 years the layer of greenhouse effect gases has thickened, causing more radiation reflected to earth, increasing global average temperature. This raise has changed climate regulations, giving origin to climate change.

Main effects of climate change on the road network:

- more flooding and erosion - a challenge for drainage systems and erosion protection and for the design and maintenance of culverts and bridges;
- landslides and avalanches: occurring more frequently, at new locations and with a higher share of “wet” landslide types such as slush avalanches and debris flow;
- droughts and high summer temperatures may represent problems for the asphalt surfacing, due to softening, but also for runoff conditions, due to lower permeability. Risk of wildfires may also increase in the southernmost regions;
- deterioration of roads and pavements - as expressed by the service life and rutting, mostly in cases where the drainage is insufficient. Additionally, this represents a risk for road users because the water stays on the surface causing the aquaplaning effect for the cars provoking traffic accidents;
- effects of sea level rise for coastal stability and sufficient elevation for roads, quays, and bridges as well as entrance levels for sub-sea tunnels;
- heavy snowfall in mountain areas of northern Europe causing trouble for winter maintenance and operation under difficult conditions;
- the need for better risk management and efficient procedures for initiating remedial actions after an unwanted event occurs - due to the fact that present protective measures may not be sufficient and that the planning of remedial measures requires time.

All of these effects can be recognized in all phases of road management: planning, design, construction, maintenance and operation.
3.3. FLOODS

In the whole world, flooding is one of the biggest disasters that has had a strong impact in countries economics. Flooding events may be considered in some point as man controllable, depending on land usage near rivers. The main factors influencing flood occurrence are:

3.3.1. Natural phenomena

*Seasonal rain:* It is the one with established periodicity.

*High intensity rain:* It is the one that fall in great amount in a short period of time, it is the kind of rain that has a high probability of causing flooding.

*Presence of an atmospheric phenomenon:* Rainstorms, cold fronts, hurricanes, these may easily become strong atmospheric changes, producing storms or rains of short duration, but with high intensity and frequency. This originates a considerable increasing in river flows and the eventual overflowing.

*Swells:* May be produced by hurricanes or storms, as well as extraordinary tides, which may cause flooding.

*Dam breaking:* Dams may be natural or artificial, and both are exposed to failure, causing destructive flooding.

3.3.2. Man-made phenomena

*Hydrological basin alteration:* It is due to forest deforestation. This action leaves the ground without a vegetal layer. Without vegetation, rainwater cannot be retained, or filtered, so it drips over the ground towards the rivers and ravines, increasing the flow and producing floods.

*Inadequate hydraulic structure design:* Bridges, channels, drainage, are designed without a future vision, and because of the high rate of urban development, deforestation and river pollution among others, loose their course capacity, leading to overflows, flooding and infrastructure destruction with the first rains.

*Urban development planning:* Due to urban development, rivers and ravines have been affected in many ways, urban areas send pluvial waters to this flows increasing their level. Additionally infiltration is practically zero, because vegetation has been substituted by pavement, metal or asbestos.

3.4. EFFECTS OF FLOODS ON ROADS - MEXICO'S SITUATION

Because of its geographical location, Mexico, is one of the most vulnerable countries to damage due to climate change; therefore the risks that threaten highway infrastructure are increasing. Illustration 8 shows all the hurricanes in the Pacific and Atlantic Mexican oceans in the period 1895-2007. Damage suffered by a significant part of Mexican highway infrastructure in late 2013, caused by Ingrid and Manuel storms, also demonstrated this vulnerability.
Illustration 8 - Hurricane tracks in the Pacific and Atlantic Mexican oceans in 1895-2007

3.4.1. Ingrid and Manuel Storms

Description of the natural phenomenon

Hurricane Ingrid was one of two tropical cyclones, along with Hurricane Manuel, to strike Mexico within a 24 hour period, the first such occurrence since 1958. Ingrid was the ninth named storm and second hurricane of the 2013 Atlantic hurricane season. It formed on September 12th in the Gulf of Mexico from a broad disturbance that also spawned Manuel in the eastern Pacific. After initially moving westward toward Veracruz, Ingrid turned north-eastwards away from the coast. Favourable conditions allowed it to attain hurricane status on September 14th, and the next day Ingrid attained peak winds of 140 km/h. Subsequently, increased wind shear weakened the convection as the storm turned more to the northwest and west. On September 16th, Ingrid made landfall just south of La Pesca, Tamaulipas in north-eastern Mexico as a strong tropical storm, and dissipated the next day.

Ingrid and Manuel provide yet another example that not only strong hurricanes cause disasters. Tropical storms can cause a considerable amount of destruction from flooding rainfall. This is particularly the cause with slow-moving storms or storms that move into regions with mountainous terrain like Mexico, where rainfall is enhanced.

Precipitation levels

Interacting with Hurricane Manuel on the Pacific coast and the broad cyclonic flow, Ingrid dropped heavy rainfall across eastern Mexico, primarily in Tabasco, Veracruz, and Tamaulipas states. In Tuxpan, Veracruz, rainfall totalled 511 mm (20.1 in) over 10 days, while at the Presa Vicente Guerrero dam in Tamaulipas, precipitation reached 502 mm (19.8 in). Surface runoff from the storm spread to the Pacific coast of Mexico, producing flooding in Guerrero in combination with Manuel. The impacts from both storms produced 162 billion m³ (5.7 trillion cu ft) of water, the equivalent of filling every dam in the country.
3.4.2. The flood

The disaster

The combined effects of hurricanes Ingrid and Manuel affected about two-thirds of Mexico. The rains from Ingrid caused flooding and landslides across Mexico, causing many rivers to rise, and isolating towns. In Veracruz State alone, the rains flooded 68 rivers, which damaged 121 roads and 31 bridges, including 2 destroyed bridges.

Damaged infrastructure roads

Heavy rainfall and floods damaged 1,052 roads. The most damaged highway was Cuernavaca-Acapulco with 20 landslides at the kilometres 284, 353, 304, 312, 318 and 328, as shown in illustration 9. There was also damage to some bridges; Papagayos Bridge and the bridge on the Guerrero-Oaxaca highway had partial collapse. The Coyuca de Benitez Bridge was completely destroyed (illustration 10), leaving 30 communities out of reach. In Sinaloa State the rainfall damaged more than 1,300 kilometres of highways, which represent 30% of the total highways in the state and 60 bridges. Table 11 shows highlights of damage to roads in Mexico.

<table>
<thead>
<tr>
<th>TABLE 11 - HIGHLIGHTS OF DAMAGE TO ROADS IN MEXICO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total closure</td>
</tr>
<tr>
<td>Severe damage</td>
</tr>
<tr>
<td>Total kilometres affected</td>
</tr>
<tr>
<td>Total bridges with damage</td>
</tr>
<tr>
<td>Collapsed bridges</td>
</tr>
<tr>
<td>Repair costs</td>
</tr>
</tbody>
</table>

Illustration 9 - Cuernavaca-Acapulco highway

Illustration 10 - Coyuca de Benitez Bridge
3.4.3. Lessons learned

Climate change is modifying the actual risk levels and therefore challenging design rules and procedures for the operation and maintenance of the road infrastructure. There will be an increase in unusual climatic events with significant impacts on infrastructures, operations and the economy at large. For road owners, adaptation to climate change should be included in current and future procedures covering all aspects of road planning, design, maintenance and operation.

Risk mitigation

For landslides immediate actions were necessary to allow the road being in operation. For instance, all private constructors lend machinery to government to remove landslides in main roads, although in some points it was necessary to build bypass. The bridges damaged have been reconstructed with stronger design and better materials. These engineering solutions were defined according to the risk identified and considering adaptation to climate change, in order to minimize the effects in highway infrastructure for future events.

As budget restrictions must be taken into account, the implementation of solutions was prioritized considering the most vulnerable infrastructure according to the probability of occurrence and impact.

All this actions help to mitigate risk. However, there is still some risk remaining. This risk can be transferred to insurance. This policy insurance works as a financial tool to face the economic losses that represent damage to infrastructure for those risks that cannot be avoided.

4. WEB-BASED RISK MANAGEMENT MANUAL

4.1. INTRODUCTION

PIARC (World Road Association) Technical Committee on Risk Management for Roads (TC 1.5) developed a web-based Risk Management Manual/RM-Manual, which is a useful knowledge database designed to introduce road risk management technologies and their practices in the world. The main purpose of this manual is to foster practice of technologies against road risks among the road communities, because of urgent need to share ideas on how to manage the risks due to natural and man-made hazards and climate changes. The RM-Manual consists of a Toolbox, Archives and Links (Illustration 11). This manual will be released on Internet in 2016.
4.2. BACKGROUND

There are following needs to develop the Web-application Risk Management Manual:

1. need to create a space for PIARC members to share ideas about road risk management tools: the risks to roads caused by natural and man-made hazards and climate changes are increasing, creating an urgent need to share ideas on how to manage those risks. Built within the web-application is the ability for PIARC members to create topic specific blogs on current road risk issues;

2. need to provide a central repository: the web-application is configured to allow PIARC members to upload, download, categorize, search, print, and sort a container of risk management tools and information. The web-application is also has a built in function to search the web for other risk related materials. The web-application allows PIARC members to make better-informed decisions on which tools best fit their needs. TC 1.5 would establish quality control guidance and standards for uploading information to the risk management database.

4.3. OBJECTIVE OF RISK MANAGEMENT TOOLBOX

The RM-Toolbox objective is a useful knowledge database designed to introduce and share the risk management technologies and their practices among PIARC countries. The purposes are to introduce of basic RM techniques to the road sector systematically, to popularize road RM technology in developing countries, and to utilize the RM-Toolbox as a common property of PIARC. The larger purpose of the web site is to foster a community of practice for technology against road risks.

4.4. SYSTEM OF RISK MANAGEMENT MANUAL

System of Web-based Risk Management Manual is designed to access the database application through Internet Web browser around the world. We choose the open source of free software package Easy PHP as database application, which is one of useful database packages consists of free software applications and provides a module named Drupal as Content Management System/ CMS. The version and software applications of Easy PHP are as follows:

    / version : Easy PHP 5.3.5.0
    / Web server: Apache 2.2.17
    / language: PHP 5.3.5
    / database: MySQL 5.1.54

Drupal is a CMS software platform where we can browse and edit the Web-based Manual database through Web browser. The security update of Drupal, which has been supported continually by many voluntary programmers in the world, will guarantee the security of the Web-based Manual after release to PIARC Website.

4.5. WEBSITE OF RISK MANAGEMENT MANUAL

The Web-application of RM-Manual was designed with a user friendly and graphical interface to the road risk management SQL Database. There is also a robust search engine, point and click directly, and faceted search that make finding information easy:
• search function: Search using relevant terms to find contents from all subjects both in the RM-manual and in other external Websites by robust search engine;
• point and click directly to see contents in the RM- Manual database such as Inventory sheets and Archives;
• study and search/focus function: Refer Files using faceted search in order to focus on objectives in the toolbox of RM-Manual in any optional order of risk management process, project phase, road facilities, natural disaster, or man-made disasters.

The web-application was built using free, open source software (Drupal, mySQL) via a server hosting service. Using a web-application provides an easy, centralized, always accessible, and uncomplicated method for PIARC members to contribute risk management techniques and examples to the database of RM-Manual.

4.6. STRUCTURE AND CONTENTS OF RISK MANAGEMENT MANUAL

Illustration 12 shows the start screen of PIARC Risk Management Manual.

![Illustration 12 - Start screen of Risk Management Manual](image)

The RM-Manual consists of Toolbox, Archives and Links (Illustration 11). These three contents are provided on the left top pull-down menus of the start screen, so that these contents can be an effective database.
4.6.1. Toolbox and Inventory Sheets

Illustration 13 shows the screen of the Toolbox. In order to access proper answers for your road risk management from many subjects of inventory sheets in the toolbox, you can either browse faceted search on the left top or use search in this site on the right top.

Toolbox provides technologies to manage road risks due to natural and man-made hazards. It includes inventory sheets that aim to assist budgeting and road management with easy application of risk management technologies/tools. They are classified according to risk management process, project phases, road facilities, natural disasters and man-made disasters.

Risk management process is classified further into:

1. general,
2. communication and consultation,
3. establishing context,
4. risk assessment,
5. risk treatment, and
6. monitoring and review according to ISO 31000: 2009.

Project phases are also classified into:

1. general,
2. plan,
3. design,
4. construction, and
5. operation and maintenance.
Road facilities are classified into:

1. general,
2. bridges,
3. tunnels,
4. slopes,
5. earth works, and
6. others.

Natural disasters are classified into:

1. general,
2. earthquake,
3. storm surge/tsunami,
4. volcano,
5. flood/heavy rain,
6. windstorm,
7. snow/freeze,
8. landslide/rock fall/debris flow, and
9. others.

Man-made disasters are classified into:

1. general,
2. direct hazard, and
3. indirect hazard.

Faceted search shown in *Illustration 14* can find proper inventory sheets with step-by-step search in any order through risk management process, project phases, road facilities, natural disasters, or man-made disasters. Search in this site on the right top can search related subjects by relevant terms in the overall manual.

*Illustration 14 - Screen of Faceted Search*
Inventory sheets that are included in the Toolbox are menus prepared to disseminate the risk management technology used mainly in Japan and in New Zealand to developing countries, and the risk management technology/tools from different countries will be added to them. The inventory sheets aim to assist budgeting and road management with easy application of risk management technologies/tools. The inventory sheets, which concern techniques for managing the risks associated with natural and man-made hazards, are useful in each road management/project phase, i.e., planning, design, construction, and operation and maintenance. In each phase, the sheet makes a brief presentation of the proposed recommended methodology and of the technologies available.

The Toolbox currently includes 126 inventory sheets and practical example files in order to help researchers and practitioners with different kinds of risk management such as assessment, treatment, acceptance, and communication. Illustrations 15 to 21 show several samples of the inventory sheets.

4.6.2. Archives

Archives introduces useful documents for road risk management and case studies on strategies that have been effective in road risks. Archives is a menu involves previous TC activity reports, useful documentations of TC members for road risk management, case studies documenting strategies that have been effective in avoiding or mitigating road risks, and so on.

4.6.3. Links

Links is a menu linked with other external web site resources relating to information or publications on road risk management such as PIARC website, RM-manuals and RM-publications for roads.

4.6.4. Create or Add new content

The web-application will allow registered PIARC members to upload road risk management files in RM-Manual, and to continue building a vibrant and engaged risk management community. PIARC members could create or add new contents such as new Risk Inventory Sheets into Toolbox and forum topics into Archives.

Illustration 15 - Example of inventory sheet (Road disaster prevention hazard map using GIS)
Illustration 16 - Example of inventory sheet (Tsunami signal planning)

Illustration 17 - Example of inventory sheet (Slope framework)

Illustration 18 - Example of inventory sheet (Earth removal work)
Illustration 19 - Example of inventory sheet (Bridge deck collapse prevention)

Illustration 20 - Example of inventory sheet (Tunnel inspection using a laser scanner)

Illustration 21 - Example of inventory sheet (Universal scenario method, Risk matrix)
4.7. FUTURE DEVELOPMENTS OF WEB-APPLICATION RISK MANAGEMENT TOOLBOX

The RM-Manual is required as a part of the PIARC association’s web-based knowledge base for dissemination of basic risk management techniques in the road community, especially in developing countries. Therefore, TC1.5 is preparing to release the web-based RM-Manual into PIARC web site for PIARC members in 2016. PIARC members could access here, and use the knowledge database of RM-Manual by an easy, always accessible, and uncomplicated method to contribute risk management techniques and examples.

- The Web-application will allow registered PIARC members to connect to the RM-Toolbox, and upload new risk management files;
- PIARC members will be able to enrich Risk Management Information with articles such as RM topics, Risk inventory sheet, RM manual, Case studies related to crisis management and emergency management, Case studies collected during the past cycles, etc. Especially, current TC 1.5 members will be required to add inventory sheets on RM for adaptation to the climate change effects to the toolbox.

Ultimately, TC 1.5 will be responsible for facilitating the process and getting PIARC members to contribute contents to the RM-Manual via the web-application. The relevant PIARC technical committee, heir to TC 1.5, will be responsible for maintaining the software of the web site.

4.8. CONCLUSIONS

The Web-based Risk Management Manual, which was developed by the Technical Committee TC1.5, is a useful knowledge database designed to introduce and share the risk management technologies and their practices among PIARC countries. The Risk Management Manual consists of a Toolbox, Archives and Links. PIARC members could create or add new contents such as new Inventory sheets into Toolbox and forum topics into Archives. It will be accessible through PIARC Website and will be maintained by a technical committee.
5. CONCLUSIONS

The major conclusions of this report may be summarized as follows.

Chapter 1 gives an overview on methodologies for risk management of road infrastructure and their classification into methodologies on object and on strategic level. Furthermore possible climate change related threads and resulting impacts for road infrastructure are described. This compilation supports owners and operators in identifying vulnerabilities and their impacts and gives information on the consideration of these aspects in their infrastructure management. In summary it can be stated that owners and operators need methods that allow an easy and low cost initial assessment of the existing infrastructure with regard to possible hazards from climate change and climate change related extreme weather conditions. It is important that these approaches can be used on the basis of already existing infrastructure data. Initial approaches that on object and network level have been identified and are listed as examples in chapter 1. However, it is also clear that a full integration of these risk-based approaches as part of a holistic asset management approach does not yet exist.

In chapter 2, we proposed a practical system to systematically evaluate damage risks to road facilities by natural disasters and conducted a case study on a section of the national highway. The proposed procedure particularly focuses on the quantitative evaluation of risks to various road facilities from various disasters by using a common index, and incorporates both threats and opportunities into the analysis. Opportunities are favourable outcomes incidentally resulting from the implementation of road disaster prevention measures. Based on the idea that prevention of damage by implementing a road disaster prevention measure is the effect of the measure, we examined the priority of measures from the viewpoint of the ratio of the measure effects to its cost. Although further detailed study will be necessary to improve the rating of the likelihood of hazards and their consequences, which has been introduced to make the quantitative evaluation of risks in our study, the proposed procedure is helpful in prioritizing road disaster prevention measures by comparing the impacts of various disasters on various road facilities.

In chapter 3, we made an overview and described the consequences of climate change and how storms cause damage to infrastructure. It is necessary to use preventive methods to adapt road infrastructure to climate change, and the need of developing a better risk management process that covers all aspects of road planning, design, construction, maintenance, and operation is recognized. The lessons learned show that risk management is a process that must be permanent, continuous and needs to be adapted to the new weather conditions. In the first place risks need to be mitigated, and for the remaining portion of risk which cannot be avoided, we recommend applying insurance to risk transfer, as one of the possible solutions.

In chapter 4, we developed a web-based Risk Management Manual. This manual was designed to access the database application through the Internet. We chose an open source software package Easy PHP as the database application, and Drupal was adopted as a content management system (CMS). Drupal is a CMS software platform by which we can browse and edit the risk management manual, and it is used worldwide. The proposed web-based risk management manual is user-friendly and is equipped with a graphical interface. The risk management manual is composed of toolbox, archives and links, and the toolbox further includes various inventory sheets. Inventory sheets are easily searched either by search engine or by faceted search menu.
6. REFERENCES


APPENDIX 1 - MUDFLOWS IN ALPINE REGIONS

1.1. INTRODUCTION

Mudflows appear at certain weather situations in alpine regions. These slides are very dangerous, because they appear without early warning. Settlement areas und infrastructure is endangered. The formation of a mudslide depends on different factors.

An alpine mudflow, called Mure in the Alps, is per definition a slowly to fast flowing suspension of water, solid material and wild wood, if large quantities of bed load get available in a short time. The solid fraction is higher than 40% [Technische Richtlinie für die Wildbach- und Lawinenverbauung, Fassung 2011, Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management].

The most significant factor for mudflows is heavy rain. In many cases it needs only the short time of a thunderstorm to form a mudflow. Such a thunderstorm has a rainfall mass of more than 60 l/sqm in half an hour. Also important is the bed load. It reaches from fine sand up to big rocks. The bed load must be available very fast. The danger is very high, if the material is wet down to the bedrock, after previous rainfalls or snowmelt. River bank breaks und landslides bring also a lot of bed load. The third big influence is wild wood. Wild wood is broken wood from the trees near the river, deadwood, rootstocks or whole trees sliding in the riverbed after a riverbank break. All these wild wood is lying in the riverbed. If the water level rises, the wild wood is swept away until the next narrow point. At the narrow point the wood is stopped and builds a dam (illustration 22).

Illustration 22 - Wild wood piled up at a narrow point

Behind the dam the water is rising up more and more. If the pressure is too high, the dam breaks down. The gush of water mobilizes the bed load, an alpine mudflow is born.

A single mudflow is called mudflow hit (Murstoß). Often a mudflow has some hits, like a tsunami. The speed of a mudslide depends on the slope and narrowness of the valley. The speed can be very high. Rivers often look like a bobsled after a mudflow (illustration 23).
Illustration 23 - Mudflow washed out a river

The volume of a mudflow does not depend on the size of the river. Small dry falling alpine ditches can also build a big mudflow, because the deposit of wild wood is easy. Illustrations 24 to 27 show some examples.

Illustration 24 - Little mudflow

Illustration 25 - Mudflow spilled a house
Illustration 26 - Transport of large wood

Illustration 27 - Large mudflow buried a valley
1.2. CASE STUDY OF MUDFLOWS ON JUNE 21, 2012

a) Region

The first hotspot was the A9 between Rottenmann and Kalwang, and the second hotspot was the A10 between Flachau and Tauerntunnel north (illustration 28).

Illustration 28 - Map of motorways of Austria with incidence points.

b) History

The winter 2011/12 was rich in snow. The total snow depth in this winter was more than 7 meters in Flachau. Approximately the same amount of snow fell in the region of the A9. The snowmelt needed time until June. The layer of earth was wet down to the bedrock.

Between June 16 and 21, 2012, Central Europe was lying in a strong southwest airflow. Hot and wet air masses came from the Mediterranean Sea. A cold front from the low-pressure area over Great Britain and Spain started to sweep the warm and wet air mass away on June 20. First heavy heat thunderstorms took place on June 20 in the eastern alpine regions of Austria and brought a lot of rain. Sunny and dry weather started on June 21, 2012 all over Austria. The temperature rose very fast to 30°C by very high air humidity. After midday first thunderstorms were active along the Central Alps, especially in the area of the A9. Already these thunderstorms brought a lot of rain. Until the evening, new thunderstorms arose again and again. The exact amount of rain is unknown. The nearest observation stations detected around 100 l/sqm. The rainfall in the core area must have been much higher. In the south, the thunderstorms brought large hail (6 cm).
Numerous mudflows and high water in the bottom of the valley were caused by this intensive rain fall along the A9 between Rottenmann and Kalwang (Illustration 29).

Illustration 29 - High water in Paltental along Motorway A9

Three big mudflows destroyed some houses. Many villages were evacuated. In the evening, a mudflow from a small ditch near Gaishorn spilled the A9 (Illustration 30). Two cars drove into the mud, three people were slightly injured. The motorway was closed until the next morning, since in darkness danger could not be assessed.

Illustration 30 - Mudflow buried Motorway A9 near Gaishorn am See.
At the A10 a very big mudflow spilled the motorway after 8 p.m. A car was caught from the mud and pushed against the middle crash barrier (Illustration 31). The driver could not leave the car and was critically injured by the mud. The man was rescued by the fire brigade. The front passenger could help himself, with minor injuries. Also the A10 had to be closed. This mudflow moved approximately 1 million cubic meters of bed load.

Illustration 31 - Mudflow buried Motorway A10 near Tauern tunnel

Two main alpine transit routes were closed, additionally the subordinate roadwork and the railway. The traffic had to be diverted extensively.

The next morning, geologists evaluated the situation. After the execution of protection activity, the A9 could be opened again. One direction of the A10 could also be opened the next day at midday.

During the next weeks, bed load had to be removed from all motorway protective structures (Illustration 32). More than 300,000 cubic meters of bedload had to be put away by trucks to landfills. The two mudflow areas got new protection structures.

Exactly one month later, on July 21, 2012, a second large mudflow event happened between at A9 Rottenmann and Kalwang. The village of St. Lorenzen im Paltental was destroyed completely. Some people were injured. The protection structures protected the A9 motorway from mudflows.

Illustration 32 - Cleanup of Motorway A10 near Tauern tunnel
1.3. Protection structures

Austria has a long tradition of protecting his living space and infrastructure. It has over 150 years of experience. There is an organisation to handle these problems; it is called Wildbach- und Lawinenverbauung (torrent and snow slide control). This organisation is a part of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management.

There are different ways to protect the motorway. The next pictures show some solutions. The structures are designed for an incidence with a frequency of 150 years.

a) Bedload barrage

These plants shall keep back the bedload (*illustrations 33 and 34*).

*Illustration 33 - Bedload barrage after a mudflow*

*Illustration 34 - Empty basin with a rake*
b) Ballast sedimentation basin

This construction shall keep back the mud, to protect rivers on the valley ground to get too much sediment. Deep rivers protect the villages near the river against high water (illustration 35).

Illustration 35 - Filled ballast sedimentation basin.

c) Wild wood rake

This plant shall hold back the wild wood, to protect against log jams (illustration 36).

Illustration 36 - Wild wood rake in action
d) Mudflow breaker

This plant shall break the enormous power of a mudflow (illustration 37).
APPENDIX 2 - PROJECT MANAGEMENT METHODOLOGY (PRINCE2)

PRINCE2 is a project methodology which one of its components is the management of risk. Illustration 38 shows the processes and components of PRINCE2. PRINCE2 definition speaks about controlled environments. A project methodology has for goals to maximize the percentage of success. Evaluate the risk and forecast the answers in case it happens enables to control the project environment. PRINCE2 methodology puts forward the necessity to define clearly the environment specificities for each project in order to avoid to be caught unprepared when an event occurs.

Illustration 38 - PRINCE2 processes and components

PRINCE2 operates with a risk analysis procedure including five steps: identify, assess, plan, implement and communicate, as shown in illustration 39.

Illustration 39 - Risk management procedure
In the identification stage, we first introduce the context of the project; that is, all the information we have about the project. This information enables to understand the risks for each goal that has been given. For each risk raised, we identify its cause (the event or situation which produce the risk), the event that should result and the positives and negatives effects of the risk (opportunities and threats). After the identification, the risks are appreciated. We assess the probability of an event to occur and evaluate the impacts of these effects on the project by the risk analysis matrix, which is shown in illustration 40.

![Illustration 40 - Risk analysis matrix](image)

Then, a list of responses are planned to face the risks, limit the threats and exploit the opportunities. We can classify all the techniques to manage the risk in four categories:

- avoidance (eliminate, withdraw from or not become involved);
- reduction (optimize - mitigate);
- sharing (transfer - outsource or insure);
- retention (accept and budget).

Finally, we implement the responses that had been planned when a risk materializes. It operates through the nomination of responsible people to monitor the risks and execute the foreseen responses. One document, named Risks Strategy regroups all the information to deal each risk. This document evolves throughout the project in order to manage the new identified risks. The step communicate continues all over the project. It aims to inform the stakeholders of the identified and assessed risks and of the planned and executed responses. This communication is realized through project documents such as Progress Reports, End Stage Reports, End Project Reports and Feedbacks.

The PRINCE2 project methodology has been customized to manage the road works in the Brussels-Capital Region, Capital of Europe.
APPENDIX 3 - DISASTER COUNTERMEASURES FOR LOCALIZED AND TREMENDOUS HEAVY RAINS IN JAPAN

In Japan, 70% of national land are classified into temperate monsoonal climate in addition to mountainous or hilly areas. Japan has much rainfall throughout the year. Therefore, safety against sediment disaster continues to be an important task. It becomes a key event for subsequent road safety management such as the Hidagawa bus accident that killed 105 people in 1968 (illustration 41).

Illustration 41 - Hidagawa bus accident (08/18/1968)

Road risk management inspection conducted once in every 5 years and traffic regulation based on rainfall amount were established as a trigger of the accident. These road risk management systems have been operated in a half century. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has focused on constructing countermeasures against sediment disaster within the predetermined road traffic regulation sections or areas need for measures. On March 2014, 27,000 national routes need some sort of countermeasures, and measures were implemented at around 62% of the routes.

Illustration 42 - Recent status of road closure on national highway
The number of the sections of traffic regulation with abnormal climate was 210 around the country in 1969 when the traffic regulation system started. Some regulation sections with confirming safety were deregulated thereafter. 175 road sections with 980km long were traffic regulation sections with abnormal climate in March, 2015, which is equivalent to around 4% of the total national road length. 3,311 road closures were conducted in the previous decade, for a total time of 131,202 hours (illustration 42).

46% of the road closures were due to heavy rain. 1,891 times road closures, accounting for about half the total number, were conducted before a disaster. UP to now, continued construction of disaster prevention facilities resulted in reducing disasters by one-third within the traffic regulation sections with abnormal climate in about 30 years between 1979 and 2011 (illustration 43).

On the other hand, over 50mm/h heavy rain in a remarkably short time tends to be growing in frequent in recent years. The heavy rain is 1.3 times as frequent as three decades ago (illustration 44).
63% of disasters within the road traffic regulation sections occurred before starting traffic regulation according to statistics for national roads. On the other hand, there is a decreased incidence of disaster after traffic regulation, so called "irrelevant regulation" (illustration 45).

Based on facts, MLIT started revising rainfall criteria for traffic regulation, in order to increase the rate of traffic regulation before a disaster, and reduce the various impacts on social activity by reduction of regulation hours. We think that rainfall criteria is taking into account not only existing amount of consecutive rainfall from start raining but also amount of rainfall per hour enables proper traffic regulation against heavy rain in a remarkably short time. Simultaneously, existing criteria, amount of consecutive rainfall from start raining, will be re-evaluated and regulation time will be optimized.

Both increasing the rate of traffic regulation before a disaster and decreasing around 20% for stopped road can simultaneously be achieved within 175 regulation sections, according to simulation with disaster and rainfall record (illustrations 46 and 47).
MLIT starts to introduce new criteria to 24 sections on trial. Around 25% of total number of national road disasters occurred within the predetermined road traffic regulation sections which occupy around 4% of total national road length. Without the predetermined road traffic regulation sections, rate of disaster occurrence is low per total road length but 75% of total disasters occurred. For outside of the predetermined road traffic regulation sections, combination existing disaster prevention construction and traffic regulation are planned to optimize road traffic safety by making a database of disaster and inspection in heavy rain records.

Reference:
Document of Council for Improvement of Infrastructure, MLIT, April 2014.