

# Disaster Risk Management in the Transport Sector

*A Review of Concepts and International Case Studies*

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# Acknowledgements

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# Glossary

<b>AASHTO</b>	American Association of State Highway and Transportation Officials	<b>LEED</b>	Leadership in Energy and Environmental Design
<b>ADB</b>	Asian Development Bank	<b>LLFA</b>	Lead Local Flood Authorities
<b>APEC</b>	Asia-Pacific Economic Cooperation	<b>LRF</b>	Local Resilience Forums
<b>ATC</b>	Automatic Train Control	<b>MCA4 Climate</b>	Multi-criteria analysis for climate change
<b>BRR</b>	Badan Rehabilitasi dan Rekonstruksi	<b>MPO</b>	Metropolitan Planning Organisation
<b>CBA</b>	Cost-Benefit Analysis	<b>MTA</b>	Metropolitan Transit Authority
<b>CCRIF</b>	Caribbean Catastrophe Risk Insurance Facility	<b>NARUC</b>	National Association of Regulatory Utility Commissioners
<b>CDB</b>	Caribbean Development Bank	<b>NHIA</b>	Natural Hazard Impact Assessment
<b>CRR</b>	Community Risk Register	<b>NFIP</b>	National Flood Insurance Program
<b>DBST</b>	Double-Bound Surface Treatment	<b>NGO</b>	Non-governmental organisation
<b>DFID</b>	Department for International Development	<b>NHT</b>	Natural Hazards Team
<b>DOT</b>	Department of Transport	<b>NJ</b>	New Jersey
<b>DRM</b>	Disaster Risk Management	<b>NPV</b>	Net Present Value
<b>DRMP</b>	Disaster Response Management Plan	<b>NYCDOT</b>	New York City Department of Transportation
<b>DWR</b>	Disaster Waste Recovery	<b>NYS</b>	New York State
<b>EIB</b>	European Investment Bank	<b>O&amp;M</b>	Operations and Maintenance
<b>EIRR</b>	Economic internal rate of return	<b>PIP</b>	Policies, Institutions and Processes
<b>EME2</b>	Enrobé à Module Élevé 2	<b>PPP</b>	Public-private partnership
<b>EPSRC</b>	Engineering and Physical Sciences Research Council	<b>RIA</b>	Regulatory Impact Assessment
<b>EU</b>	European Union	<b>SADC</b>	Southern Africa Development Community
<b>FFSL</b>	Fortified for Safer Living	<b>SARCOF</b>	Southern Africa Regional Climate Outlook Forum
<b>FHWA</b>	Federal Highway Administration	<b>SCIRT</b>	Stronger Christchurch Infrastructure Rebuild Team
<b>FMTAC</b>	First Mutual Transportation Assurance Company	<b>SCTIB</b>	South Carolina Transportation Infrastructure Bank
<b>FUTURENET</b>	Future Resilient Transport Systems	<b>SUDS</b>	Sustainable Urban Drainage System
<b>GE</b>	General Electric	<b>TA</b>	Technical Assistance
<b>GLA</b>	Greater London Authority	<b>TAM</b>	Transportation Asset Management
<b>GIS</b>	Graphical Information System	<b>TIGER</b>	Transportation Investment Generating Economic Recovery
<b>HOV3+</b>	High-occupancy vehicle (3 person)	<b>TIP</b>	Transportation Improvement Program
<b>HRA</b>	Hot Rolled Asphalt	<b>TTL</b>	Task Team Leader
<b>IBHS</b>	Institute for Business and Home Safety	<b>ToR</b>	Terms of Reference
<b>ICT</b>	Information and communications Technology	<b>UK</b>	United Kingdom
<b>IDF</b>	Intensity-Duration-Frequency	<b>USA</b>	United States of America
<b>INA</b>	Infrastructure Needs Assessment	<b>UNISDR</b>	The United Nations Office for Disaster Risk Reduction
<b>IPA</b>	International Performance Assessment	<b>VfM</b>	Value for Money
<b>IMC</b>	IMC Worldwide Ltd.	<b>WB</b>	World Bank

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# Executive Summary

## Background

Natural hazards regularly impact the performance of transport systems and their ability to provide safe, reliable, efficient, and accessible means of transport for all citizens, especially in emergency situations. Despite the frequency of natural hazards, and the threat of more extreme and variable weather as a result of climate change, there is still no systematic approach to addressing natural disasters in the transport sector and there is little knowledge that has been disseminated on this topic. This report offers a framework for understanding the principles of resilience in transport. It provides practical examples, gathered from an extensive secondary literature review and interviews, of the measures that transport professional can implement in transport projects.

This report represents a first effort within a broader activity to mainstream resilience in transport projects. Follow up work will focus on i) producing a short and practical road map for World Bank Task Team Leaders and Transport professionals to guide actual steps to mainstream resilience in transport projects, and ii) creating more linkages between this work and the broader ongoing work within the World Bank on disaster risk management frameworks, and with references to relevant external sources.

## Approach for mainstreaming resilience

Transport is a complex adaptive system with multiple modes and assets at different stages of their lifecycle, and upstream and downstream interdependencies with other infrastructure systems, including water, Information Communications and Technology (ICT), energy, and the built environment. These manmade assets interact in turn with the natural assets in their environment. All these manmade and natural assets and systems are delivered, maintained, operated, and regulated by a range of agents and institutions. The complex interactions between these different physical, social, economic, and institutional elements are often non-linear, chaotic, and unpredictable. Unknown risks can also emerge over time and

cascade throughout the system.

The following are guiding principles that should inform the identification, planning and design of transport projects by donors and the owners, investors, and managers of transport infrastructure in developing countries:

- 1. Shift from an “asset-based” approach, which sees transport as a set of discrete assets, to a “systems-based” approach, which looks at the interactions between the technical, social, economic, and organizational components of a transport system over time.** A common failure characteristic that emerged from the case studies reviewed was the failure of systems to be treated and planned as systems, resulting in significant damage to transport infrastructure. The case studies have shown that critical infrastructure components had different capabilities, redundancy was lacking, levels of protection were incomplete or missing, the responsibilities for infrastructure were weak and divided, and there was a misplaced optimism in the “robustness” of infrastructure to withstand all hazards. When planning and designing resilient infrastructure, the focus should not just be on the artefact but also the people and processes, governance structures, resources, and knowledge that set and shape its resilience. The implication is that the opportunities to introduce and mainstream resilience in the transport sector begin upstream, with the institutions, policies, regulations, processes, and practices that determine where, how, and what infrastructure is planned and designed. Rather than talk about a “resilient bridge” we should talk about a “resilient crossing” (RUSI conference 2014). Instead of first looking at the transport asset and asking how to make it resilient, the first questions to ask are: What is the purpose of this project? Is it in the right place? Is it at the right time? And what is the resilience of the rest of the system within which it sits? A system is only as strong as its weakest link; be this physical, environmental, social, economic or institutional.

**Table 1: Risk versus resilience approaches (adapted from Park et al., 2012)**

<b>Risk management</b>	<b>Resilience</b>
Risk analysis calculates the probability that known hazards will have known impacts	Resilience analysis improves the system's response to surprises and accepts uncertainty, incomplete knowledge, and changing conditions
Bottom-up analysis assesses impact of hazards on components' critical functionality	Top-down analysis assesses interdependencies and interactions at a system level
Assesses the impact at one point in time	Includes a temporal dimension
Minimizes probabilities of failure	Minimizes consequences of failure
Strategies include robustness, strengthening, oversizing	Strategies involve adaption, innovation, flexibility, learning, diversity, redundancy, safe failure

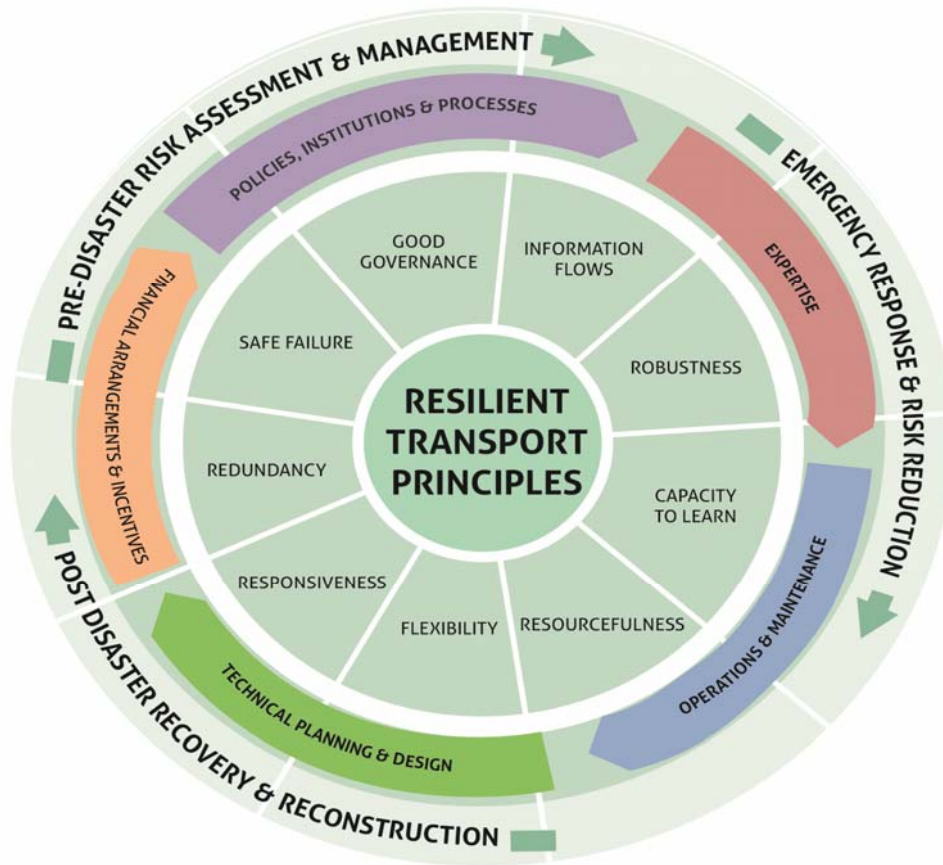
**2. Operationalize the concept of resilience and use this to complement risk analysis when planning, appraising, designing, and evaluating transport projects.** Risk and resilience approaches are complementary. Risk analysis looks at the impact of an adverse event on the critical functionality of specific components in a system whilst resilience approaches look at the entire system's behavior over time, both before, during, and after a disaster. Resilience analysis, unlike risk analysis, focuses on improving the performance of a system in a wide range of unexpected hazards, rather than only reducing known risks. It focuses on minimizing the consequences of failure and improving the ability of the system to maintain functionality and recover quickly after a known or unknown shock or stress. Systems can exist with low risks and low resilience, and these even may perform the same as systems with high risks and high resilience (Linkov et al., 2014). In developing countries, high-risk events (a large earthquake or tsunami) dominate the attention of donors but it is often low-risk events (small landslides and localized flooding) that "bleed" the system and have the greatest accumulative economic impact.

**3. Identify and engage with the many stakeholders who own, manage, and influence the resilience of transport systems before, during, and after disasters.** Vertical and horizontal

coordination, information sharing, and engagement between all these stakeholders are needed to mainstream resilience throughout the transport sector. The stakeholders are diverse and could include: Infrastructure owners, which may be private or public; regulators; Investors and insurers; transport and other infrastructure system operators; government departments—transport, finance, environment, agriculture and forestry, planning and infrastructure, energy, ICT, water, home affairs (emergency services, including police, ambulance, fire rescue service, and the military); local authorities; meteorological offices, climatologists and other scientists; universities and research centers; emergency responders; engineers; maintenance crews; contractors and construction workers; communities; and other international donors.



**Figure 1:** Illustration on analytical framework for mainstreaming resilience in the transport sector.



## Analytical Framework for Mainstreaming Resilience in Transport Systems

Figure 1 represents an analytical framework to guide thinking on resilience in the transport system. This framework addresses the three key levels that need to be addressed when identifying problems and challenges in a transport system and identifying, planning, designing, and evaluating transport projects. The outer circle represents the temporal dimension of resilience. These are the three key stages of the Disaster Risk Management Cycle—pre-disaster risk assessment and management, emergency response and risk reduction, and post-disaster recovery and reconstruction. The inner circle shows the five domains where resilience needs to be introduced—policies, institutions and processes; expertise; financial arrangements, and incentives; operations and maintenance; and technical planning and design. The innermost circle has the nine

principles of resilience that should be introduced across these domains and stages.

Whilst measures have been divided by the different stages of a DRM cycle, any policies, processes, and mechanisms to improve emergency response and post-disaster reconstruction will need to be considered and implemented ex ante, and not during or after a disaster. The principles of resilience are explained further in the main report.

**Table 2: Summary table of domains and resilience principles in the transport sector (Source: IMC Worldwide)**

DOMAINS	RESILIENCE PRINCIPLES
<p><b>Policies, Institutions, and Processes (PIPs)</b></p>	<p>PIPs are the policies, institutions, processes, and regulations for embedding resilience into a country’s infrastructure systems and assigning responsibility for risk management. PIPs need to embody and promote principles of good governance and encourage horizontal and vertical information flows throughout the system. Plans and processes should be flexible and encourage responsiveness and resourcefulness. Institutions should also have the capacity to learn from past failures, and processes and policies should be put in place to encourage this. PIPs can also encourage redundancy in the diversity of transport options and routes as well as redundancy in emergency operating processes and plans. Furthermore, PIPs that encourage multi-modal and multi-agency coordination are necessary so that the principles of safe failure, robustness, and flexibility are taken into account in the technical planning and design of infrastructure systems.</p>
<p><b>Expertise</b></p>	<p>The capacity of all agents—government officials, operators, engineers, emergency personnel, regulators and the community—needs to be developed to institutionalize and mainstream resilient processes. Agents should be educated in the principles of good governance in infrastructure systems and trained in how to collect, exchange, and use information. They should also be encouraged to be flexible to changing circumstances, showing responsiveness and resourcefulness in their ability to mobilize assets and resources as well as respond rapidly and effectively during an emergency.</p>
<p><b>Financial arrangements and incentives</b></p>	<p>Adequate resources and incentives are needed to plan, design, and construct resilient transport infrastructure. Financial arrangements and incentives need to be flexible, exhibit responsiveness, and embody the principles of good governance.</p>
<p><b>Operations and Maintenance (O&amp;M)</b></p>	<p>Processes of operating, maintaining, inspecting, and monitoring transport assets are essential for ensuring the robustness of infrastructure. They are also useful for collecting and storing information on infrastructure performance, which provides the capacity to learn from past failures and to possibly detect early deteriorations. O&amp;M processes should also encourage responsiveness and resourcefulness, and emergency procedures defined so that agents can identify problems, establish priorities, and restore function quickly after a failure.</p>
<p><b>Technical planning and design</b></p>	<p>Technical planning and design measures are not add-ons and cannot be addressed in isolation from the other domains. By planning and designing for safe failure, robustness, and flexibility it is possible to mitigate the vulnerability and exposure to hazards, as well as minimize the severity of consequences when damage or failure occurs. The severity of consequences can also be minimized by providing for extra redundancy in the system as this will help emergency personnel access areas in a disaster and help the system recover faster.</p>



# Important Aspects of Encouraging Resilience in Transport Systems

Below are examples of the important aspects that need to be considered across the domains and DRM cycle to build resilience in transport systems.

## Pre-Disaster Risk Assessment and Management

- **The principle that a system is only as strong as its weakest link requires a central agency, which can coordinate and mediate the responsibilities across the system.** The United Kingdom, for example, has published a National Infrastructure Plan every year since 2010 to set a crosscutting and strategic approach to plan, fund, finance, and deliver infrastructure. This holistic approach has been furthered by the establishment of bodies to coordinate between government, industry, regulators, NGOs, emergency responders, infrastructure owners, and operators, such as UK's Natural Hazards Team and New Zealand's Regional Engineering Lifeline groups. New initiatives have also been launched to conduct assessments of the UK's critical infrastructure assets. The UK's Infrastructure Research Initiatives Consortium, for example, has developed a National Infrastructure Model (NISMOD) for national assessment of infrastructure performance, which has been developed into an interactive "infrastructure visualization dashboard."
- **The uncertainty and unpredictability of hazards, as well as the large number of interdependencies within a transport system, requires a design approach that is sensitive to the environment and the performance of the whole network over time.** Meyer (2008) recommends adopting "systems perspective in network-oriented design" and "risk-oriented probabilistic design procedures" in order to allow a more explicit trade-off between the cost implications of a more robust design and the resulting performance of the infrastructure. A level of risk can then be determined that is acceptable to society given the criticality of the asset and the local conditions. This opens up more design options, for example, choosing a less robust design and designing instead for flexibility, safe failure or redundancy. Another key consideration in such design is defining the functional requirements of the system. Design standards can also be supplemented by performance-based standards—which set the time it should take to recover service—and therefore capture the broader and more temporal dimensions of resilience.
- **The resilience of transport systems to natural hazards has a determining influence on key transport performance indicators, such as reliability, safety, and cost effectiveness, and should be specified as a key goal and objective in transport planning.** Hazard mitigation and climate change adaptation should be integrated within transport plans through the greater use of hazard mapping tools and contextually appropriate design approaches. Setting resilience as a key transport objective also goes hand in hand with an approach that seeks to understand the role of the asset in the network and its contribution to the economy and community. This will necessarily entail a greater consideration of the principles of redundancy, safe failure, diversity, and flexibility in the development of transport plans.
- **Understanding who owns the asset and defining the role of various parties in mainstreaming resilience within the transport system, and infrastructure as a whole, is a critical part of DRM policy development.** Economic regulators have a role to play in ensuring incentive and penalty reflect the real costs from failures, though this may not be an effective lever in less well-regulated countries.

The private sector is increasingly an owner and operator of infrastructure in developing countries and business continuity plans for private operators are a useful instrument with which to mainstream resilience. Local authorities are also another important player. Due to the localized impact of hazards on infrastructure, as a result of varying micro-climates and exposure/ sensitivity, local authorities must also be involved in assessing and determining the resilience of local transport systems. Those at the frontline operating, responding, and witnessing the damage and failure of transport infrastructure—emergency responders, local communities, maintenance crews—are a further invaluable source of knowledge that should feed into policy development and the planning and identification of projects.

- Data on natural hazards and the condition, reliability, and performance of existing infrastructure assets are vital for the appropriate planning and design of infrastructure.** Information on natural hazards and the development of hazard maps can be sought through innovative means such as crowdsourcing initiatives and arrangements for open data sharing between key stakeholders. The insurance industry, for example, has the most comprehensive dataset on hazards and a number of initiatives, including RMS' partnership with the United Nations Office for Disaster Risk Reduction (UNISDR) and the World Bank, have developed to provide governments with open access to their data and catastrophe models. Data on the performance of infrastructure and the root causes of any damage/disruption/failure can best be recorded through transport asset management systems. This data is also a useful tool for generating market pressure and incentivizing behavior change amongst infrastructure owners and operators. Given the trans-boundary nature of most disasters, it is also important that this data is shared between countries; for example the Southern African Regional Climate Outlook Forum continued to exchange information amongst forecasters, decision makers and climate information users even when Mozambique and South Africa were close to war in the 1980s.
- Innovative financial arrangements are needed to incentivize resilience, which both requires cross-sector coordination and, typically,**
- greater initial investment costs, though these will be recouped over the lifecycle of the asset.** Infrastructure banks can encourage a more holistic and strategic vision for infrastructure system. Grants can also include resilient selection criteria, such as the US TIGER Discretionary Grants, to promote projects that minimize lifecycle cost and improve resilience. Interdependencies, where the actions of one agency have downstream impacts on the resilience of transport infrastructure, typically create a free-rider problem that can only be addressed through greater budget coordination. Japan, for example, has cost-sharing mechanisms between public works organizations and DRM organizations to share the cost of raising the height of expressways, which can provide useful evacuation routes.
- Project identification, preparation, and appraisal standards are critical tools for explicitly prioritizing, measuring, and building in resilience at the project level.** Appraisal models should evaluate the costs of infrastructure damage, failure, and service delays from disasters, and this should be reflected in feasibility reports and the planning and design options. The scope of projects should also be expanded to include the role of neighboring land-use practices and upstream land management; practices that are significantly more cost effective than raising the height of a bridge, for example. Environmental impact assessments are a particularly useful tool, which can be expanded to include the impact of disasters on infrastructure, as recommended by the EU and implemented in Australia, Canada, and the Netherlands.
- In order for new tools, design approaches, and standards to be adopted and implemented there needs to be a greater awareness amongst all stakeholders of the need for resilience and what it entails.** The resilience of transport infrastructure ultimately rests on the availability of a good standard and broad spectrum of expertise within government departments at the regional, national, and local level, and within transport project teams. The community can also, where feasible, be trained to monitor and inspect transport infrastructure and flag early warning signs.



Loma Prieta earthquake damage on Bay Bridge, California, in 1989.

## Emergency Response and Risk Reduction

- **The period immediately during and after a disaster involves restoring critical lifeline routes and regaining basic access and mobility so that society can quickly resume a basic level of functionality and transport departments can begin examining how to “build back better.”** Transitional traffic measures are introduced, rubble and debris are cleared from any priority routes, and damaged infrastructure is temporarily patched to prevent further damage. This process is simpler for infrastructure that has been designed for safe failure as the modes of failure will have already been predicted and designed in.
- **Redundancy, diversity, flexibility, and robustness are among the key principles of resilience that must be considered in advance in order to ensure an effective recovery phase.** Creating redundancy within the physical network as well as within emergency operating systems and critical infrastructure systems, such as electricity, is critical, as is increasing the diversity of transport modes and the flexibility of modes and routes (e.g., adding capacity to modes and routes and identifying emergency routes, critical nodes, and alternatives). The robustness of priority lifeline routes, assets (including vehicles, fuel supplies, communications equipment, repair facilities, ferry vessels/terminals, and airport landings) and emergency equipment (mobile pump units, fuel, spare parts, materials, Bailey bridges, generators, battery backup systems) is another aspect to consider. Furthermore, in order for these assets and equipment to be operational, critical personnel must be available during an emergency and contingency plans established to identify or mobilize temporary staff. Finally, rapid response demands immediate funding (index-based catastrophe bonds, for example) and a greater degree of budget flexibility. For example, funds can be diverted from existing programs or tendering processes shortened.
- **One of the most critical resilience principles to consider for an effective recovery is the availability of relevant and timely information, and the capacity to respond rapidly to this information and mobilize the required assets and resources.** Horizontal and vertical information networks should be established between transport operators (e.g., inland railways and roads linking to ports), agencies (e.g., between environment, weather, and transport agencies, as well as ICT, energy, and transport), and across jurisdictions. This requires the development of good working relationships and



A Maryland Emergency Management Agency press conference on Hurricane Sandy.

coordination processes, which can sometimes be formalized into memorandums of understanding or mutual aid arrangements. These information flows must also exist between transport operators and users, and plans should be developed for centers to coordinate the disruption amongst operators and disseminate travel information to transport users. This enables the disruption to be managed effectively and safely, as well as limits any further damage to the infrastructure through the introduction of transitional traffic measures.

- **Transport operators, agencies, and jurisdictions must coordinate not only to share information before and during a disaster, but also ensure that the assumptions upon which their disaster contingency manuals are based are accurate.** Coordination should be ongoing and contingency manuals and backup plans discussed and reviewed on a regular basis in order to facilitate an effective response. Communication procedures between these agencies must also be regularly reviewed to ensure that any problems and inefficiencies are identified and exercises planned with key staff to assess and strengthen their capabilities.

## Post-Disaster Recovery and Reconstruction

- **Successfully “building back better” after a disaster requires a number of pre-disaster arrangements to establish an enabling environment for rapidly coordinating, funding, assessing, contracting, and rebuilding damaged infrastructure.** A number of challenges plague this period, and threaten to re-establish or even create new vulnerabilities: land tenure issues, poor data collection and management, inadequate funding, conflicting donor and country regulations, lack of communication and coordination, fragile construction markets, the absence of clear policies and guidelines, and the need for speed, compromising satisfactory fiduciary control and accountability, as well as “building back better.” Effective disaster response planning is seen with Japan’s approach to governance structures, financial arrangements, and emergency procedures described in the report and annex, which led to the rapid recovery of transport operations after the 2011 Great East Japan Earthquake. Embedding the principles of responsiveness, good governance, and flexibility through the development of pre-disaster arrangements is a crucial first step to mitigating these risks and developing a contextually



appropriate response.

- **Mechanisms for improving the coordination between national and local governments, infrastructure systems, transport operators, and the private sector can be established and considered pre-disaster.** For example, establishing framework agreements with the private sector with agreed rates, roles, and responsibilities, allows rapid mobilization and effective risk sharing, which will save time, cost, and resources. Systems can also be established for cross-agency information sharing and data storing, such as the establishment of a data steward—a point of contact—at each agency for sourcing data, and the distribution of pre-established dataset guidelines for collecting data post disaster. Data on the condition and performance of the damaged infrastructure, both before and after the disaster, is particularly critical for post-disaster reconstruction and these systems can be established in advance.
- **Financial tools can encourage pre-disaster planning and a shift from a “like for like” approach to reconstruction towards “building back better.”** Pre-agreed relief and recovery measures, thresholds for funding, and cost-sharing agreements can provide funds more rapidly and be tied to conditions that can therefore incentivize pre-disaster mitigation strategies. Betterment funds, which have been deployed in Queensland, can bridge the financial gap between the cost of restoring infrastructure to its pre-disaster standard and the cost of enhancing infrastructure resilience. Disaster insurance can offer a vehicle for mainstreaming resilience by providing insurance for post-disaster reconstruction on the condition that there are demonstrable pre-disaster planning initiatives to ensure effective use and management of funds post disaster; a system that has been adopted by the African Risk Capacity insurance pool, for example.
- **By definition, the need for flexibility in the post-disaster reconstruction period means that not all guidelines and contracting arrangements can be prescribed prior to a disaster, but will also need to evolve through an assessment of the scale of the damage and the needs of the community.** For example, after the 2011 earthquake in New Zealand the scale of the damage and uncertainty around the scope of the

works prompted the formation of an alliance arrangement between public and private organizations. Alliance contracting can further the collaborative approach between responders by sharing risks and rewards measured against pre-determined performance indicators. These arrangements, along with the introduction of greater flexibility in the design standards and reconstruction guidelines, allowed private sector responders to maximize value for money in reconstruction and prioritize funding where there was the greatest need. Nevertheless, the need for flexibility can be instilled prior to a disaster through greater capacity building and the development of a strong organizational ethos and a deep understanding of the principles of resilience.

- **The capacity to learn, exercise, and review within and across organizations, should occur both during “normal” times and after a disaster has occurred.** Performance must be monitored continually during reconstruction and appropriate performance indicators selected to capture the quality of this progress. The US’ Interagency Performance Evaluation Task Force after Hurricane Katrina in 2005 is an example of an effective approach to learning lessons on the institutional economic, policy, financial, and legislative lessons that led to the disaster



Road damage after a dam breach at Havana Ponds in Rocky Mountain Arsenal National Wildlife Refuge.

# 1. Introduction

## 1.1 Background

A significant body of research exists on the role of low-carbon and sustainable transport in mitigating climate change, however, there has been relatively little information to date on what measures can be implemented to mitigate the physical impacts of natural hazards on transport infrastructure and minimize the severity of the consequences when a disaster does occur.

Roads, railways, airports, and ports are the back-bone of the local and national economy. However, in the event of natural hazards, these connections and links are frequently severed. The cost of repairing or reconstructing damaged infrastructure puts enormous financial pressure on governments, which in developing countries are already struggling with scarce resources and poor capacity. It also has severe economic and social impacts on the businesses and communities that rely on this transport infrastructure in order to survive.

Furthermore, failure results in a number of immediate fatalities and injuries, which can increase as emergency responders are unable to reach affected communities and the delivery of aid is delayed. The Haiti earthquake in 2010 highlighted the vulnerability of a centralized

transport  
system,  
which is  
reliant on  
key

hubs that can easily be damaged. Damage to the airport and key port affected the speed at which resources could be brought to Haiti. Whilst other ports were operational and less affected by the quake, they were reliant on good transport links themselves.

## 1.2 Purpose

This report sets out the principles of resilience in transport and examples of the practical measures that can be included in projects to mainstream resilience across multiple domains and across the Disaster Risk Management (DRM) cycle. It also provides illustration of how resilience can be included within projects through a review of a number of case studies around the World.

### EVIDENCE 1: Impact of natural hazards on transport infrastructure

**USA, Hurricane Sandy, 2012:** The Metropolitan Transportation Authority estimates that Sandy caused USD 5 billion in losses: USD 4.75 billion in infrastructure damage and USD 246 million in lost revenue and increased operating costs (CNN, 2013).

**Nepal, Kosi flooding, 2008:** The Kosi flooding in 2008, which resulted from an embankment breach (the flow of water at the time was just 1/7<sup>th</sup> of the



system design flow), caused damage to 79 percent of roads in Bihar, India, and immediately cut off Nepal's East-West Highway interrupting the flow of goods and services in Nepal and affecting medical referrals to the main hospital at Dharan. It took a full year before the East-West Highway was fully restored and surfaced by the Nepal Department of Roads.

**Mozambique, flooding, 2000 and 2013:** Flooding in 2000 caused USD 47 million worth of damage to the road system, with estimates for repair valued at USD 87.2 million (World Bank, 2000). Again in 2013, flooding at a similar scale caused an estimated USD 80 million worth of damage to paved roads and bridges (not including unpaved roads), with estimated costs for short-term repairs given at USD 52.30 million, whilst medium to long-term interventions were estimated to require USD 68.85 million (Aide Memoire 2013).

**Solomon Islands, earthquake and tsunami, 2007:** Costs from the 2007 disaster in the Solomon Islands were estimated at USD 591.7 million, which represented around 90 percent of the 2006 recurrent government budget.

## 1.3 Methodology

This study draws on a large body of knowledge from both developed and developing countries, including a review of reports on transport infrastructure resilience from several developed (USA, UK, EU and Japan) and developing countries. There are a number of evidence boxes throughout the report to support the recommendations with examples from countries around the world.

An analysis of 26 case studies was conducted covering both developed and developing countries. They are examples of good practice and were drawn from already documented case studies, interviews, and Worldwide experience. They provide examples of transport measures across the phases of pre-disaster risk assessment and management, emergency response and risk reduction and post-disaster recovery and reconstruction. Each one reviews the issues related to Policies, Institutions, and Processes (PIPs); Expertise; Financial Arrangements and Incentives; Operations and Maintenance (O&M); and Technical Planning and Design and these are presented in color-coded boxes for readability (see Annex).

A pragmatic methodology was employed in the selection of these case studies given the shortage of documented practices related to resilience in the transport sector. Many derive from developed countries since they have been driving innovative actions in this area, however, this does not invalidate their relevance for developing countries. The approaches embody key principles of resilience, such as improved coordination and knowledge sharing, which are also key components of institutional strengthening and development projects.

## 1.4 Report Structure

**Chapter 1** introduces the objective and scope of this study, while **Chapter 2** examines the properties of transport infrastructure systems and how a disaster can occur and propagate through these systems when a natural hazard, big or small, occurs.

**Chapter 3** explains and compares key terms and concepts, including resilience, risk, and robustness. These concepts are frequently used, but they have often become umbrella terms, which encompass a multitude of meanings. Opportunities to introduce innovative approaches for increasing the resilience of infrastructure can be missed if these concepts are uncritically used at the project design stage. In the drive for cheap/quick delivery these concepts also risk getting lost during the implementation stage.

**Chapter 4** presents a framework for assessing resilience and risk to the transport sector from natural hazards.

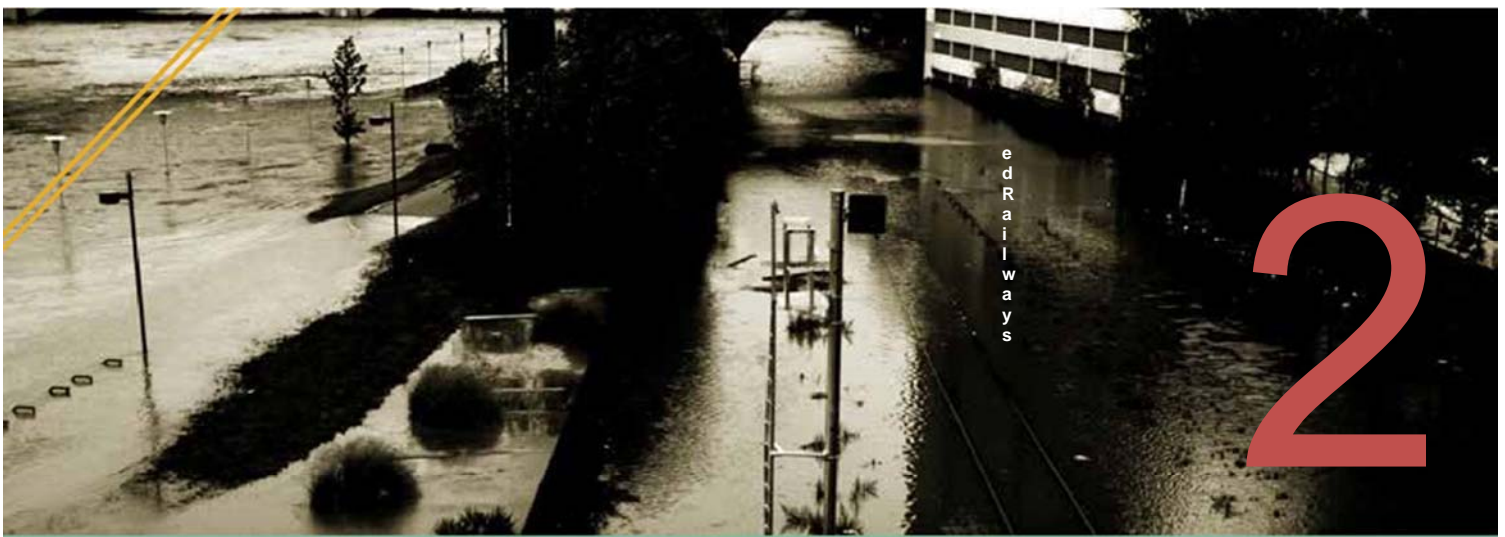
**Chapter 5** provides examples of the range of actions falling under the five key elements of the transportation resilience framework: Policies, Institutions, and Processes (PIPs); Expertise; Financial Arrangements and Incentives; Operations and Maintenance (O&M); and Technical Planning and Design. These will work to encourage planning, design, construction, operations and maintenance of resilient transport infrastructure, in the pre-disaster phase.

**Chapter 6** focuses on principles to apply during and

immediately after a disaster, during the emergency response phase. It additionally provides examples of the actions that will encourage faster and more resilient response and recovery in the transport sector during a disaster. Many of the actions during emergency should be well thought of and planned before the disaster, to be properly deployed when it occurs.

**Chapter 7** discusses the post-disaster and repair of critical infrastructure to a basic state of functionality sufficient to allow **recovery**, followed by the **reconstruction** of infrastructure, which builds in the lessons learned from previous performance, such that community resilience is enhanced against future disasters.

**Annex:** The Annex consists of technical assessment sheets that cover the planning and design measures for each infrastructure type—roads, railways, bridges, tunnels, airports, ports and inland waterways—and for each type of hazard—geophysical (earthquakes, landslides and tsunamis), hydrological (flooding, flash floods, and mudflows), climatological (extreme temperatures and wildfires), and meteorological (cyclones, storms, and wave surges). It also includes 26 in-depth case studies, which cover pre-disaster risk assessment, emergency response, and post-disaster reconstruction measures in the transport sector.



## 2. Transport Infrastructure Systems

### 2.1 Transport Systems

Physical man-made infrastructure originates and exists in socio-economic contexts and interacts with the surrounding social, economic, financial, political, manufactured, and ecological environment. Transport is a particular form of infrastructure where this is evident. Transport networks have developed over long periods of time and evolved into a patchwork of physical networks consisting of varied transport links and modes, and old and new infrastructure with different design lives. These are governed by multiple institutions and actors, both public and private, with different funding streams, regulatory authorities, operations and maintenance processes. Transport infrastructure also sits within a large natural environment, the responsibility for which often rests with other institutions and actors.

In order to understand the behavior of transport infrastructure and why “disasters” occur it must be seen and modelled as a *complex adaptive system*. A system is defined as complex when its behavior cannot be reduced to the properties and behaviors of its individual components. The technical, human, organizational, and societal components of the system interact in complex and unpredictable ways. Risks can emerge through these interactions across different

Complex *adaptive* systems are also characterized by their capacity to self-organize and adapt in response to the feedback received from the environment (Mortimer, 2012). Transport systems have this capacity for adaptation as they include decision makers, infrastructure providers, and users who will “adapt” to changing circumstances.

### 2.2 Interdependencies

Transport infrastructure is a complex system, which in turn interacts with other complex infrastructure systems, including power, communications, fuel etc. These systems have their own design standards, and institutional and actor networks.

Interdependency refers to the mutual functional reliance of essential services on each other (see Figure 1). There are multiple types of interdependencies, which do not simply result from physical proximity (see Annex Section 8.3 for a tool for assessing infrastructure interdependencies through stakeholder engagement).

- **Physical interdependency** occurs when the operational output from one infrastructure affects another, such as power generation facilities that feed the pumping facilities that are used during subway flooding.
- **Cyber interdependency** occurs when an infrastructure depends on data transmitted through ICT infrastructure. For example, signalling on railways and the use of ICT for emergency response.

- **Geographical interdependency** is the physical proximity of infrastructures; utility lines are often collocated with bridges, roads, and rail lines, for example.

- **Organizational interdependency** occurs when the state of an infrastructure depends on the other as a result of policy, financial, governance, and organizational links. They may also be organizationally linked through shared governance, oversight, and ownership (Engineering the Future, 2013).

Interdependencies can be both upstream and downstream. For example, upstream interdependencies for the transportation sector could include power failures, which cause signalling problems for the railway. Downstream would be those systems and utilities affected by a failure in the transport network. Upstream interdependencies are important for considering the identification of hazards for the transport sector, whilst downstream interdependencies should be considered for assessing the criticality of the transport network under analysis (Hughes, J. F., and Healy, K., 2014).

**EVIDENCE 2: Hurricane Sandy interdependencies**

Hurricane Sandy is a good example of the interconnectedness of infrastructure systems and the cascading failures that will occur at the time of a natural hazard. It particularly highlights the transport sector's reliance on electricity and fuel. The combination of electricity outages and damaged refineries and terminals disrupted the fuel supply chain. Many transportation owners and operators did not have sufficient backup generation resources to last the power outage. Key disruptions included:

- Electricity outages disabled railways signals and could not support floodwater pumping systems.
- The New York City subway system had its own pump system for normal drainage but did not have dedicated backup generators, and the spares that were brought in were insufficient.
- LaGuardia airport had more than 15 million gallons of water and five pump houses had no electricity or backup generation. Subway tunnels and depots did not have the capacity to pump out water,

Figure 2: Utility Network Interdependencies: This diagram was produced by NARUC (2005) to illustrate the interdependencies between utility networks.

multiple sustainability objectives in the design of

which damaged electrical and communications systems. Furthermore, the salt water corroded equipment that could not be cleaned on site due to the potential for short-circuiting or fire. The lack of power and fuel slowed the process of replacing or taking the equipment elsewhere.

Source: Lau, C. H., and Scott, B., (2013)

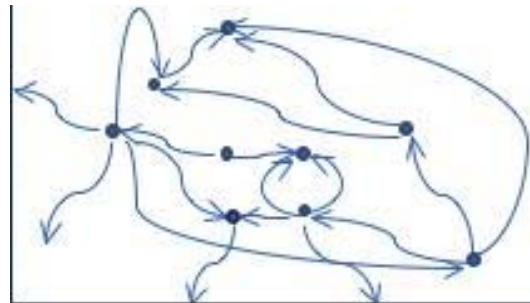


Figure 1: Systems approach figure adapted from Bartlett (2001)

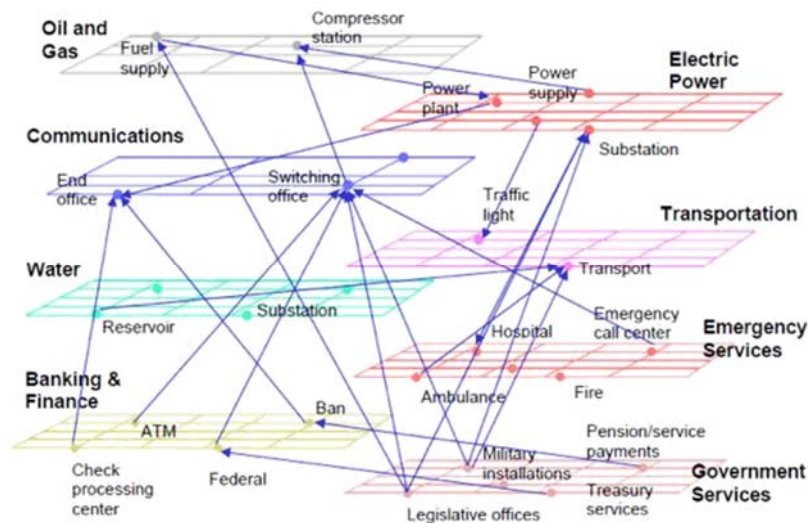
Assessing these interdependencies and adopting a systems approach opens up more strategic options for policymakers. Systems thinking is the process of understanding the relationships between components of a whole system, rather than in isolation that can often lead to unintended consequences.

An example of a systems-orientated approach and the co-benefits it can bring is highlighted in the Evidence Box 3.

**EVIDENCE 3: New York High-Performance Infrastructure Guidelines (2005)**

The Design Trust partnered with the New York City Department of Design and Construction to develop High-Performance Infrastructure Guidelines. These advocated a systems-oriented approach that focused on improving the performance of the entire roadway system and simultaneously addressing

infrastructure. These improved the lifecycle and performance of the asset, and hence its resilience to hazards, as well as additional co-benefits to public



health, safety, quality of life, energy efficiency, and sustainability.

Examples of integrated design included, designing roadways with a diversely planted media that act as a stormwater bio-retention area. This would also act as a traffic-calming device, improve pedestrian safety, dampen street noise, and improve air quality. Another example was designing a right of way with maximum shading by trees and permeable and high albedo pavements, to reduce run off, reflect light, and reduce the amount of heat absorbed by the road. This would increase pavement durability to extreme heat, as well as reduce urban heat build-up, improve air quality, and calm traffic (DTC, 2005: 9).

## 2.3 Disasters in Complex Infrastructure Systems

Disasters are never solely natural. They are the product of how natural incidents interact with aspects such as a lack of preparedness, poor capacity and adaptation, weak resilience, and over exposure and vulnerability to hazards. The exposure and vulnerability of these elements is to a great extent the result of human activity and development decisions. The relationship of these elements can be shown as the following pseudo-formula:

$$\frac{\text{Hazard} \times \text{Vulnerability} \times \text{Exposure}}{\text{Capacity}} = \text{Disaster Risk}$$

Hazards can generally be classified as “stress” events (long-term and gradual) or “shock” events and are either known or unknown. Hazards, as the disaster risk formula indicates, do not necessarily lead to disasters, but are only stressors and triggers in the system.

Failures in the transport system may not be proportionally related to, or even the direct consequence of, an external shock and can be prompted by even small hazards that push one or more elements of the system over their functional limit (see Kosi flooding, Case Study 1).

There are a range of failure modes, including simple linear failure, complex linear failure (as a result of interdependencies), and complex non-linear failure from the concurrence of unexpected events (Hollnagel 2011). A shock, such as an earthquake, can enter the system and accumulate in different non-linear feedback loops, becoming reinforced and amplified by other consequences generated by the same shock. This chain reaction ultimately pushes the overall system beyond its limits resulting in a “systems collapse.”



# 3. RISK AND RESILIENCE

# 3

## 3.1 Defining Resilience

Resilience is best seen as an emergent property of what a system does, rather than what it has. Resilience encompasses a longer timescale of analysis and acknowledges that in a complex system failure is inevitable and there will always be unknown shocks and stresses. A system may not recover to its previous state, but contains the ability to adapt, self-organize, renew, learn, innovate, and transform. This definition particularly emphasizes “bouncing forward” rather than “bouncing back” to the conditions that might have resulted in the disaster in the first place (Folke 2006). These qualities are critical in an uncertain and unpredictable environment.

Resilience refers to the ability of a system to withstand and absorb disruption (through reducing vulnerability, exposure, and increasing the system’s coping and adaptive capacities), continue to maintain functionality during an event and recover, and learn and adapt from adverse events (Chang 2009). Resilience is also a useful bridging concept between disaster risk reduction and climate change adaptation as it ties together risk mitigation and recovering from an event when it does occur (ARUP and Rockefeller Foundation, 2014).

## 3.2 Risk-based Approaches Versus Resilience

Risk analysis is a process that characterizes the vulnerabilities and threats to specific components to assess the expected loss of critical functionality. Risk management addresses the specific point highlighted in the figure on the right.

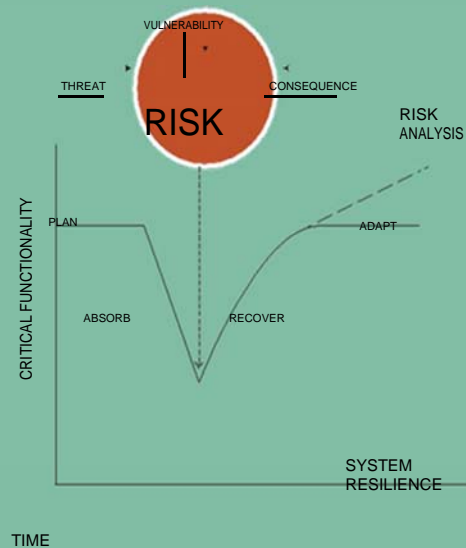


Figure 3: Risk versus resilience, adapted from Linkov et al., 2014

Two key elements of complex engineered systems pose issues for the applicability of risk assessment:

- (1) The interconnectedness of social, technical, and economic networks and the presence of path dependencies and non-linear interactions, which means that different and unexpected responses can be generated, even in response to the same stimuli at different points in time (Park et al., 2013 365); and
- (2) Unexpected extreme shocks. In the presence of known unknowns and unknown unknowns, where the probabilities, consequences, and magnitudes cannot be identified, let alone calculate traditional risk analysis techniques tend to oversimplify or ignore these ambiguities.



Risk assessment has been the central approach adopted by engineers to reduce or prevent failure by increasing the robustness of transport infrastructure.

A risk-based approach, however, tends to be inflexible and often results in fail-proof designs that are brittle and can lead to catastrophic failure when conditions change or there is a significant amount of uncertainty in the system (Folke, 2006; Park et al., 2013). In attempting to design out all failures and achieve “optimality,” risk-based approaches fail to acknowledge the uncertainties in a complex system and are ultimately not resilient to surprise shocks or stresses (Park et al., 2013).

Resilience thinking, however, addresses this issue by embracing complexity, uncertainty, and unpredictability. Resilience approaches have the following characteristics:

- Uncertainty and changing conditions are accepted; there is an acknowledgement that failure will most likely occur. This approach therefore seeks to minimize the consequences of these failures by investigating the interconnectedness of multiple domains and also looking at the temporal dimension of the effect of an adverse event on a system.

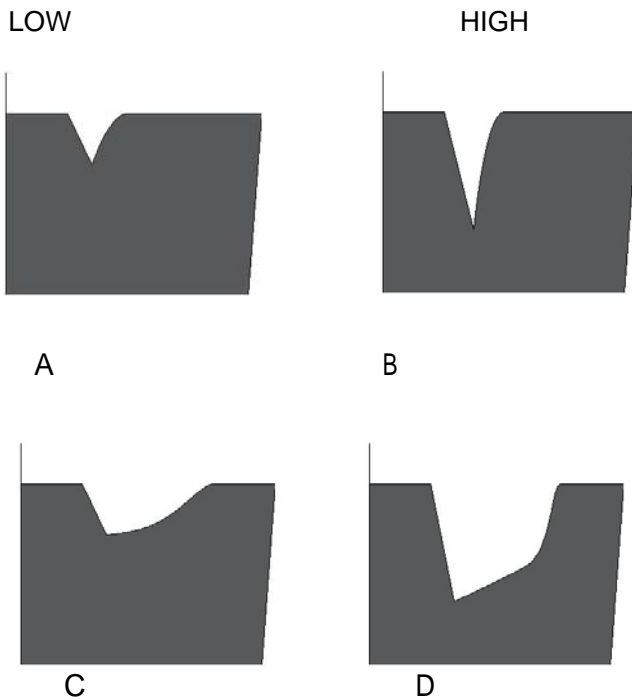


Figure 4: High/low risks and high/low resilience. This diagram shows that systems with high risk but high resilience perform better than those with similar levels of risk and low levels of resilience, and perhaps the same as systems with low risk and low resilience. (Source: adapted from Linkov et al., 2014: 407).

- Resilience looks at the “slope of the absorption curve and shape of the recovery curve” (Linkov et al., 2014: 407).
- A resilience approach involves adapting to changing conditions and designing in controlled failure (safe to fail) to reduce the possibilities of cascading failures affecting the entire system.

Risk management and resilience approaches are complementary and both are needed to build resilience in a transport system. Sometimes conflicts can arise between increasing robustness (fail-proof design) and resilience, however, this can be managed if robust structures are planned and designed with the overall system’s resilience in mind.

### 3.3 Measuring Resilience

The key challenge to combining risk and resilience approaches is developing a common understanding of how to quantify resilience, particularly given the different perspectives of resilience (ecological, socio-ecological, and engineering). The second challenge is to go beyond assessing physical coupling, which is easier to quantify, and take into account resilience characteristics and interdependencies at the institutional, organizational and economic scale (Tang and Eldinger, 2013).



Figure 5: Illustration of an analytical framework for mainstreaming resilience in the transport sector.

#### EVIDENCE 4: Transport network resilience measures

FUTURENET (Future Resilient Transport Systems) is a project sponsored by EPSRC as part of the Adaptation and Resilience to Climate Change program and led by a consortium of partners led by the University of Birmingham. FUTURENET is exploring how to measure the resilience of a transport network in terms of values recognized by various stakeholders. For example, the ratio of planned “normal” journey time to actual journey time for users of the transport system—journey delays being the defining characteristic of network resilience for typical users but other metrics can be substituted for other stakeholders. They broadly divide failure into: serviceability limit state failure, where the journey is completed but the delay is unacceptable, and ultimate limit state failure, where the journey cannot be completed. They use two types of modelling to assess these failures—detailed physical models and large-scale statistical models. These are combined to assess the effect of meteorology on traffic volumes and speed in the absence of infrastructure failure, and can determine the effect of meteorology on segments of the network and the probability they are completely severed (Bouch et al., 2012).

### 3.3.1 Quantitative Measures

Probabilistic measures of resilience tend to measure the joint probability of meeting robustness and rapidity objectives in the event of a failure in the system. There are a number of challenges in determining a network’s level of resilience. Firstly, resilience is a property that emerges from the interactions between system elements over time, rather than a property of its individual elements. Furthermore, there are few effective measures to explain the effect of transportation on the region’s economy and society and poor data at the network level. The resilience of a system also depends on whether the system meets the user’s needs in terms of journey time and reliability (Bouch et al., 2012). Yet each user has a different understanding of resilience and tolerance for failure, posing additional challenges in accurately capturing and measuring a “resilient” transport system. Finally, quantitative measures of resilience entail significant time and cost constraints and require a high level of skill and training, as well as detailed information about the system.

### 3.3.2 Qualitative Measures

An alternative is to develop a proxy for measuring resilience by identifying the qualitative characteristics of a resilient system. Whilst these are subjective, they are more flexible and involve engaging more of the key stakeholders in a system, which is an important component of identifying and planning transport projects.

Here we have presented the resilience principles, which should inform the development of a resilience assessment framework. Whilst much of the literature often categorizes these resilience principles by institutional, technical, and social dimensions, we have found, through our review of the case studies, that these principles do not map neatly onto particular dimensions and that there are a number of overlaps. For ease we illustrate how each principle applies across these dimensions using the categories: Policies, Institutions, and Processes; Expertise; Financial Arrangements and Incentives; Operations and Maintenance; and Technical Planning and Design.

### 3.3.3 Resilience Principles

The resilience principles are described in further detail below, including how they apply across the five different domains.

#### GOOD GOVERNANCE:

- **PIPS, O&M, Expertise, Financial Arrangements and Incentives, and Technical Planning and Design:** Good governance involves defining roles and responsibilities so that organizations’ functions do not overlap and there is no competition for limited financial and human resources. There should be mechanisms for integration and coordination across modes and systems, and between hierarchies and jurisdictions. This, additionally, includes public accountability, transparency, and anti-corruption measures, particularly in project selection procedures and procurement. Understanding and engaging with the resilience perspectives and concerns of different stakeholders, including private and public sector, and transport users and communities, is another important aspect of good governance.

## **INFORMATION FLOWS**

- **PIPS, Technical Planning and Design, and O&M:** Systems must exist for information to be exchanged and transmitted quickly between transportation system managers, staff, and users (across different modes of transport), as well as across multiple agencies and infrastructure systems. Efficient information flows must also exist to transmit back lessons after disasters and emergencies.

- **Expertise:** Agents (engineers, operators, government officials etc.) need reliable information derived from rigorous data collection and risk-assessment processes in order to make strategic decisions regarding transport infrastructure. They also need to be trained in how to collect and use this information.

**FLEXIBILITY** is the ability to change and evolve in response to changing conditions.

- **PIPS and Expertise:** Flexible, forward-looking, progressive plans implement change iteratively as more information is learnt about the climate or local context. Flexibility also involves agents being receptive to local knowledge and new techniques.

- **Financial Arrangements and Incentives:** Flexibility can be encouraged through financial incentives to change attitudes and experiment with new ideas. It can also be encouraged through methods such as Real Options Analysis.

- **Technical Planning and Design:** Flexibility can be introduced in asset design; provisions can be made for a bridge deck to be raised at a future date in response to increased flooding.

**RESOURCEFULNESS** is the ability to mobilize assets and resources to meet priorities and goals. This includes financial, social, physical, technological, information,

and environmental resources. Resourcefulness is “the capacity to visualize and act, to identify problems, to establish priorities, and mobilize resources when conditions exist that threaten to disrupt an element of the system” (Da Silva et al., 2012: 11). This applies across all the domains.

**RESPONSIVENESS** refers to the ability and motivation of agents to restore function and order rapidly after a failure. Rapidity, however, should not impair the ability to learn from the failure nor reintroduce previous or new vulnerabilities. This applies across all the domains.

**CAPACITY TO LEARN:** Engineers, emergency planners, transport operators, owners, regulators etc. should all be able to learn from experience and past failures. Processes should be in place to encourage reflexivity and learning from past failures and events. This includes performance evaluations, etc. and encouraging a dialogue between scientists and policymakers so that policies and design standards reflect the reality on the ground. This is true across all domains.

**REDUNDANCY** refers to spare capacity and involves increasing the diversity of pathways and options so when one fails, others that serve a similar function can substitute and take their place.

- **PIPs, O&M, and Technical Planning and Design:** Increasing network redundancy and connectivity involves increasing the number of transit routes in an area as well as the range and diversity of options; be this by walking, cycling, rideshare, car share, public transport etc. Redundancy can also be developed within emergency operations procedures so that in case emergency responders or response units are incapacitated, for example, a backup plan can be readily mobilized.



Heavy monsoon showers inundated the roads in Dharga Town, Sri Lanka, on May 17, 2010.

**SAFE FAILURE** involves designing infrastructure so that when one component fails it does this progressively with minimal disruption to other parts of the infrastructure and network. Safe failure involves accepting change and unpredictability and “controlling modes of failure” (Park et al., 2013: 363) to minimize more catastrophic consequences. This is contrary to “fail safe” designs, which assume all failures have been designed out. Safe failure is a means of achieving robustness, as it allows failure of certain parts in order to safeguard critical load-bearing parts of the infrastructure and therefore minimize the extent of the total failure.

**ROBUSTNESS** is understood as the ability of transport assets and the network to withstand stresses and shocks to a level that is designated tolerable and cost-effective. Standards of tolerability and these design standards change over time.

- **Technical Planning and Design:** Robustness can be achieved through measures that mitigate/ reduce the hazard (upstream works or bioengineering, for example), or reduce the exposure and vulnerability of transport infrastructure. Robustness of the critical load-bearing parts of the infrastructure can also be

achieved by designing the whole structure for selective/ safe failure.

- A robust transport system also involves considering the interdependencies between transport and other infrastructure systems, either by improving the robustness of these other systems (energy, water, ICT etc.) or introducing buffers (Swiss Re, 2010) that mediate the relationship between these system links so that a shock does not instantly transmit into system failure (Rinaldi, 2001).

**O&M** is key to maintaining the robustness of the transport system.

This section presents an overview of a resilience and

# 4. DISASTER RESILIENCE AND RISK ASSESSMENT IN TRANSPORT SYSTEMS

## DISASTER RESILIENCE

# 4

risk assessment framework and the key questions and instruments that should be employed at each step. Step 1 involves a high-level assessment of the resilience and risk of transport systems to identify the key challenges and needs in order to define the project scope. Once the project scope has been defined in Step 2, Step 3 assesses the resilience of the transport system using a resilience matrix tool. Step 4 proceeds to conduct a more detailed risk assessment of the project and, on the basis of the combined resilience and risk assessment, options are analyzed in Step 5.

### 4.1 Step 1: Needs Assessment

This step involves engaging with all relevant stakeholders, including government, regulators, investors, insurers, infrastructure operators from different systems and modes, local authorities, and local communities, and using the resilience analytical framework to examine to what extent the nine principles of resilience exist in the country's transportation system. This involves thinking across the five domains—PIPS, expertise, financial arrangements and incentives, operations and maintenance, and technical planning and design—and across all stages of the DRM cycle: pre-disaster risk assessment and management, emergency response, and post-disaster recovery and reconstruction.

Questions to ask include: Do the relevant institutions (transport, environment, DRM, water, infrastructure etc.) exhibit good governance and flexible forward decision making? Are there good information flows between and within institutions, at the horizontal and vertical level to aid with emergency response? Are agents in these institutions responsive, resourceful, and do they have the capacity to learn?



Figure 6: Risk and resilience assessment (Source: IMC Worldwide)

During this step it is also important to consider to what extent natural hazard risks impact short-, medium-, and long-term social, economic, and strategic development goals, plans, programs, and targets. Given resource constraints, there are often trade-offs to consider between different regions, transport priorities (maintenance, new assets, road safety) and between quality and quantity, particularly improving “basic access” and having “fewer but stronger roads.”

Further consideration should be given at this stage to the impacts of climate and extreme weather-related risks, specifically on the performance objectives of the



transport project/network. These relate to: (1) safety; (2) ensuring basic access and mobility; (3) reducing the need for regular and costly rehabilitation and reconstruction works, as well as maintenance costs; and (4) reducing the risks that transport projects may have on increasing disasters and the vulnerability of the whole network. Regular infrastructure assessments can provide a good baseline understanding of the state of the transport system and asset-management platforms can provide information on the impacts of natural hazards on transport infrastructure.

When identifying needs and challenges in the transport sector it is also critical to identify and assess the upstream and downstream interdependencies with other infrastructure systems and identify weak spots and critical points of failure that would affect the resilience of transport systems. Infrastructure assessments can also provide an invaluable baseline understanding of the state of the transport system. All these considerations and assessments should be done at the country assistance strategy stage to set the country priorities and objectives, but if this has not been done, they can be included here at the planning and implementation stage.

#### **EVIDENCE 5: Interdependency analysis**

An interdependency analysis and assessment of the resilience of the infrastructure system as a whole should be conducted. An infrastructure timeline can be constructed to compare policy, planning, and project timelines across infrastructure types allowing coordination and alignment across policy timelines. This has been developed in the UK to show at a strategic level where government departments should coordinate before and during policy development to ensure there is not a risk of failure due to interdependency (Engineering the Future, 2013). An interdependency analysis can also show when there is a risk of cascading failures if a natural hazard occurs and what are the critical points of weakness in the system and what should be addressed in future TA and construction works projects.

## **4.2 Step 2: Project Scoping**

The previous stage may have identified economic, social, political or strategic challenges and needs that

will then set the priorities for defining the project scope. However, if increasing resilience has been assessed to be a priority the project scope needs to be further defined to enable more detailed assessments to take place. This could be according to: (1) geographical areas, which are more susceptible to natural hazards, and face either a combination of high/low risks and high/low resilience; (2) historically poorly performing assets/networks or infrastructure with little remaining design life; and (3) asset criticality assessments.

Asset criticality assessments can be done through a combination of desk review and stakeholder engagement. The desk review identifies critical assets based on data such as average daily traffic, economic information, functional classification, goods movements, and emergency management. Stakeholder input can provide further information, which is not readily or publicly accessible and thus ensures that the project scope reflects local concerns. Problems with this approach are that it can be time consuming and data/resource intensive. The outcomes can also be highly subjective and depend on who is invited and the quality of the engagement. Asset criticality can also ignore the low-level risks that face an extended road network and instead prioritize high-value assets.

#### **EVIDENCE 6: Assessing asset criticality**

The FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework (2012) proposes a framework for performing asset criticality (the structural scale approach), which can be conducted either through a desk review or stakeholder input. Figure 7 shows the results. A series of maps was produced for each region showing the vulnerability ratings for roads, airports, ferries, and railways. The vulnerability ratings were mapped for all modes across the state. Red lines were where one or two areas have been found to be vulnerable to catastrophic failure; yellow, where roads are vulnerable to temporary operational failure at one or more locations; and green are roads that may experience reduced capacity somewhere along the segment (see Case Study 5 for a stakeholder input approach to assessing asset criticality).

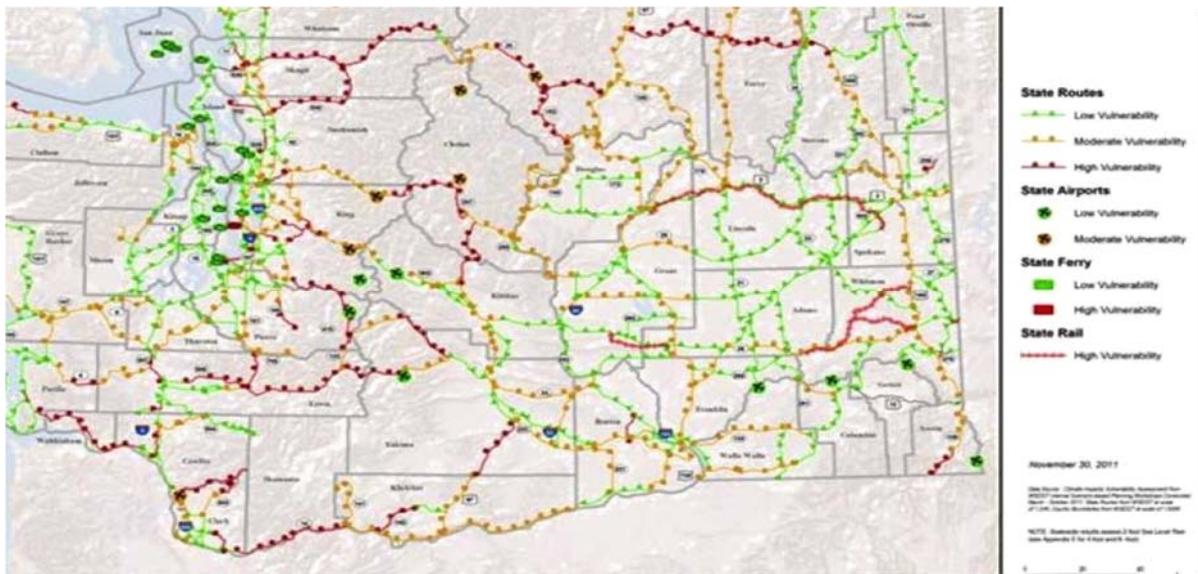


Figure 7: Washington State DOT Climate Impacts Vulnerability Assessment (reprinted with permission).

### 4.3 Step 3: Resilience Assessment

There are few models and tools that have attempted to operationalize the resilience approach, and those that do have tended to look at one domain (physical, institutional, social) rather than the interconnections between these domains. Increasing the resilience of transport systems demands coordinated solutions across these domains. A handful of models have emerged to address this; two of which are summarized below. More detailed frameworks tailored to specific usage could be developed.

Linkov et al., (2013) developed a resilience matrix to enable policymakers to coordinate solutions across different domains and across the DRM cycle. The first dimension captures the temporal aspect of resilience and categorizes the different stages of change in a system: plan/prepare, absorb, recover, and adapt. The second dimension captures the different domains that should be analyzed in a system: physical, cognitive, information, and social. Metrics are devised for each cell on the basis of literature reviews, stakeholder engagement, and the principles of resilience. The addition of a metric in one cell will inevitably affect other metrics that are included. For example, physical systems to collect data will need a corresponding metric

in the social domain to represent the ability to interpret and communicate this information. These metrics are measured both quantitatively and qualitatively by technical experts and stakeholders in the system.

	Prepare	Resist	Recover	Adapt
Traffic				
Physical	Yellow	Yellow	Green	Red
Information	Green	Green	Green	Green
Cognitive	Green	NA	Green	Green
Social	Yellow	Yellow	Yellow	Yellow
Energy				
Physical	Yellow	Green	Red	Green
Information	Yellow	Yellow	Red	Red
Cognitive	Yellow	Red	Red	Red
Social	Green	Green	Red	Green

Figure 8: Resilience matrix approach (adapted from Rosati J.D., 2014).

This matrix does not provide an absolute measure of resilience, but allows for a baseline assessment of the system by indicating gaps in the system's resilience, project needs, and the role of partners. It also provides a way of comparing project alternatives through multi-criteria decision analysis, by scoring the system against various resilience criteria such as redundancy, and aggregating these weighted scores to provide an overall resilience score for each system (Roegel, 2014).

Hughes, J.F., and Healy, K., (2014) have also recently developed a resilience assessment framework for New Zealand's Transport Authority. This is not represented as a matrix and does not capture the temporal dimensions of resilience, but captures the dimensions (technical and organizational), principles, and measures of resilience. They suggest that a criticality and risk assessment should first be used to identify the strategic and vulnerable points of a network and a resilience assessment then carried out on these high-risk and high-value assets. The issue with this is that a system with low risks but also low resilience could be overlooked.

## 4.4 Step 4: Risk Assessment

Risk is a function of threats, vulnerabilities, and consequences. This step assesses the risks to the project to determine the expected loss of critical functionality to a system.

- Context analysis: a) specify and further define the context at the scale chosen (territorial, network, section, structure); and b) establish risk criteria and indicators.
- Risk identification: a) identify threats (natural hazard variables and contextual site variables); b) identify vulnerabilities (sensitivity, exposure, and adaptive capacity); and c) identify consequences (extent and severity of disruption).
- Risk evaluation: a) construct risk scenarios and score/value consequences and likelihoods; b) rank and

prioritize consequences/ vulnerabilities (see Evidence Boxes Numbers 7 and 8).

### EVIDENCE 7: California seismic retrofit program for bridges

The California Department of Transportation after the Loma Prieta earthquake in 1989 inventoried approximately 25,000 bridges for seismic retrofitting. A prioritization methodology was designed to efficiently direct resources. The process began by establishing a required performance standard. For most the minimum standard was "no collapse" but some damage to the structure was acceptable as long as the structure remained intact and could be reopened soon after the disaster. The exceptions to this were 750 high-investment bridges, which were vital transportation lifelines. A layered screening process was then undertaken, which used four major evaluation criteria: seismic activity, seismic hazard, impact (based on attributes such as average daily traffic, route type and detour length), and vulnerability (structural characteristics). The score for each criterion was multiplied by a weighting factor—seismic activity and hazard were weighted more heavily—and summed to arrive at the total score. Source: National Research Council (2008).

### EVIDENCE 8: UK Highways Agency model for prioritizing adaptation

In the UK Highways Agency model (2011), vulnerabilities are prioritized for action according to severity, extent of disruption, uncertainty (evaluates uncertainty around climate change projections and impact of climate change on the asset/activity), and the rate of climate change. The rate of climate change is the time horizon for effects to become material. An asset life sub-indicator is included to reflect the impact that decisions will have on assets with different design lives. For example, for short-term assets, which are likely to be renewed within 30 years, it is less a priority to take action regarding climate impacts that will materialize in the long term. The prioritization of vulnerabilities in turn informs the timescale for action. The UK Highways Agency (2011) the many different locations on the network need to be treated; adaptation is concerned with a long life, expensive asset where it is suggested that there would be clear benefit from future proofing new designs now; and there is a long lead time needed to plan adaptation." (Highways Agency, 2011: 23).

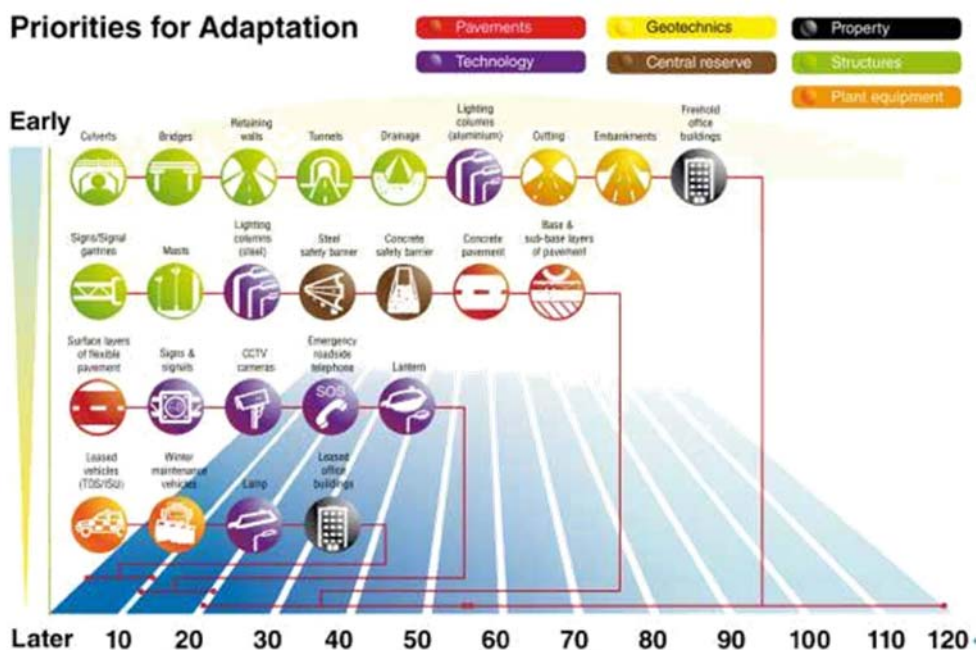


Figure 9: Priorities for adaptation of highways assets (Highways Agency, 2011: 22).

## 4.5 Feasibility Studies / Options Analysis

Following the assessment of the project’s risks and resilience, the final step involves identifying and evaluating the range of options available. This can be done through a cost-benefit analysis to generate a Net Present Value (NPV). When mitigation and adaptation policies cannot easily be quantified in monetary terms a multi-criteria analysis is a useful additional tool. In the case of significant uncertainty and the potential for flexibility, real options analysis provides an alternative to NPV assessments. The challenges and advantages of these approaches in the context of DRM are described below.

### a. Cost-benefit analysis

Costs-benefit analysis (CBA) involves comparing cost and benefit streams over time and these are then discounted to generate a NPV. There are a number of drawbacks to CBA, including the difficulty in accounting for non-market values, failing to account for the distribution of benefits and costs, and choosing the right discount rate. CBA is particularly difficult for DRM projects where the planning horizon is much longer. There is also often an absence of reliable hazard and vulnerability data, and a lack of information around the

benefits and profits of DRM projects (Mechler, 2005). Japan has, however, adapted CBA for DRM projects and used it to measure the resilience characteristics in the framework above, including redundancy and regulatory changes to improve good governance/flexible forward-looking decision making (see Evidence 9).

### b. Multi-criteria analysis

Multi-criteria decision analysis offers a structured methodology for combining quantitative and qualitative inputs from risk assessment, CBA, and stakeholder opinion to rank and evaluate project alternatives. MCA4 climate initiative ([www.mca4climate.info](http://www.mca4climate.info)) developed a step-by-step multi-criteria decision guide for countries to develop pro-development climate policy planning, and is also relevant for infrastructure resilience (Hallegate, 2011). The first level of the decision tree is split between inputs (costs of implementing a policy) and outputs (impacts of policy), which then lead to the second-level criteria: the public financing needs and implementation barriers of implementing a policy option (inputs), and the climate-related, economic, environmental, social, political and institutional impacts of policy options (outputs). The inputs are at the third level disaggregated into “minimize spending on technology,” “minimize other types of spending,” “allow for easy implementation,” and “comply with required



timing of policy implementation.” The output side is further broken down into 15 criteria covering climate-related issues, economics, environment, social, political and institutional dimensions (see Annex for decision tree). See Evidence Box 9 for a case study on sea walls and roads in the Bahamas.

#### **EVIDENCE 9: Multi-criteria decision analysis for sea walls and roads in the Bahamas**

In 1999, Hurricane Floyd, a Category 4 (in fact wind speeds were just 2 mph short of Category

5) Hurricane traversed the Bahamian islands at peak strength causing significant damage to coastal roads and wooden jetties used to access water taxis and fishing boats plying between the various islands. The majority of the Bahamian islands are low-lying coral islands rising at the coast to just a few meters above sea level. A multi-criteria decision analysis was adopted to assess the value of building a sea wall, which was large enough to withstand extreme events. Criteria were included to assess the impact of a large sea wall on the environment’s aesthetics given that the islands are desirable tourist locations, and its contribution to the community’s safety. It was decided that high sea walls would be visually intrusive and that the residents would be advised to remain inside during a hurricane so there would be no additional safety benefits from increasing the height of the sea wall. This would also be an expensive option, and the value of the asset (the road) was not significant enough to warrant this. It was decided to design the sea wall for safe failure so that the road would be over-topped by extreme wave action and sea surges but it still prevented lower-level damage to the road (see Case Study 16 for further detail).

#### **c. Real infrastructure options analysis:**

Real options analysis offers a tool for dealing with the uncertainty of climate change and seeks to value flexibility in the design of infrastructure systems. NPV ignores that managers may need to react to new information or changes in the environment and therefore undervalues opportunities that provide future options. If there is uncertainty or the potential for flexibility or learning, then real options analysis provides an alternative to cost-benefit analysis. Costs and benefits streams are still compared over time and discounted to generate an NPV, the difference with CBA is accounting for the value of flexibility. A decision tree framework maps the costs, benefits, and probabilities of different

options and a sensitivity analysis is applied to examine the implications of different climate change scenarios (HM Treasury and Defra, 2009). The TE2100 plan for the Thames Estuary in the UK adopted a quasi-option value analysis to support decision-making under uncertainty and provided a number of alternative pathways in light of the uncertain climate (see Case Study 6).

#### **EVIDENCE 10: DRM and cost-benefit analyses in Japan**

**In Japan, cost-benefit analyses are conducted for public works projects by committees consisting of academics, business, and legal experts.** These occur before projects are adopted, and then every three to five years after to evaluate their efficiency. A CBA of coastal protection works in Japan assesses the expected losses to inland properties from flooding by tsunamis and storm surges; the prevention/mitigation of damage to land and properties from erosion; the prevention/mitigation of damage by blown sands and sea spray and negative effects on daily life; the value of natural landscapes and ecosystems; and the value of using the sea coast for recreation activities etc. The costs are discounted and compared under economic efficiency decisions criteria, such as net present value, or the economic internal rate of return.

**The cost effectiveness of redundant infrastructure, which is critical in the event of an emergency, is also factored into the evaluation of options.** The evaluation considers why the project is needed on the basis of DRM considerations, numerically estimates the level of improvement (for example, shortened travel time or securing a transport link between core cities), and then compares the effectiveness amongst similar plans and projects.

**Cost-benefit analyses are additionally conducted on new regulations.** A regulatory impact analysis (RIA) assesses the costs of a new regulation—approval processes, administration costs etc.—versus the benefits of the new regulation, such as improved land-use practices and prompter evacuation. An RIA was undertaken before adopting the Act on Building Communities Resilient to Tsunami in December 2011. (Source: Toyama M., and Sagara, J., (2012).



Castellated sea wall in the Bahamas

#### d. Value for money:

Investors and donors seek to maximize Value for Money in infrastructure programming. A report by Adam Smith International (2012) noted that whilst the goal of infrastructure programming is often to produce a

tangible asset, upstream technical assistance can significantly improve downstream VfM and a VfM analysis should therefore include as many of these outcomes and impacts as possible. VfM should measure the impacts of institutional, regulatory, and capacity building programs to improve transport infrastructure resilience.

## 4.6 Producing a Terms of Reference

The terms of reference developed will need to clearly define the resilience objectives that the project or infrastructure needs to achieve and, if appropriate, the

minimum level of functionality that the infrastructure should sustain in the event of a disaster. The terms of reference will set out options to mitigate vulnerabilities across a system, or minimize and manage the consequences when failure does occur so that the transport system continues to remain functional in the event of a disaster.

The scope of services could include addressing policies, institutions, and processes; expertise; financial arrangements and incentives; and O&M procedures. Possible options to address mitigating vulnerabilities in the planning and design of infrastructure are covered in Section 5, whilst those that will minimize and manage the consequences of failure are presented in Section 6. Section 7 explores options for the post-disaster recovery and reconstruction of infrastructure. The technical planning and design features that the consultant should consider in the planning and design of new infrastructure are presented in Section 6. And the Annex, Section 8.5, contains further technical assessment sheets for consultants to review.





A U.S. Army Africa engineer views Tanzania flood damage in 2010.

## 5. PRE-DISASTER RISK ASSESSMENT AND MANAGEMENT

This section provides practical examples of the measures that can be deployed to mitigate the vulnerabilities of infrastructure to natural hazards through the introduction of policies, institutions, and processes; financial arrangements and incentives; expertise; operations and maintenance procedures; and technical planning and design measures. For measures that will minimize the consequences of failure when a disaster does occur and prevent the introduction of further vulnerabilities see Sections 6 and 7, though the majority of these measures should still be pre-planned and arranged in order to ensure that they can be rapidly deployed once a disaster strikes.

### 5.1 Policies, Institutions, and Processes

The development of policies, institutions, and processes for embedding resilience across national, regional, and local levels should first consider “who owns the asset.” Examples of the role of different parties and the measures that they can deploy to build infrastructure resilience are provided below:

#### 5.1.1 National, Regional, and Local Policies

- **The government should establish a clear long-term infrastructure strategy and guide the development of sector resilience strategies as well as define the role of parties in achieving resilience.** The development of resilience plans should include the expertise of the meteorological office; the departments of transportation, energy, housing and urban development, planning, defence, agriculture, water, environment, and science and technology agencies; disaster management; emergency responders; and local authorities (Evidence 10, 11, and 12). This vision should, in turn, be communicated to infrastructure owners, operators, investors, and insurers, as well as regulators and local authorities so that it is mainstreamed in the operation, maintenance, and improvement of transport assets (PricewaterhouseCoopers 2010; Cabinet Office 2011).

## EVIDENCE 11: UK Policy Statement on Ports

The UK's draft National Policy Statement for ports, for example, proposes that ports need to look at the 10 percent, 50 percent, and 90 percent estimates against the emission scenario suggested by the independent committee on climate change (PricewaterhouseCoopers, 2010).

- Governments can facilitate the development of resilient strategies through developing **infrastructure resilience guidelines** to guide work at all levels and ensure resilient investment is aligned with national policy.
- Governments can launch a **national infrastructure vulnerability assessment** and conduct an **interdependency analysis** of infrastructure systems (see Annex 8.3). Inventories of critical infrastructure assets can be cross-referenced with hazard maps to identify the threat from system failure. The UK and the US, amongst other developed countries, are currently exploring developing cross-sector performance indicators to capture these interdependencies.

## EVIDENCE 12: Critical infrastructure groups

**New Zealand's critical infrastructure institutional arrangements:** Regional Engineering Lifeline Groups work closely with regional emergency management and have been established to enable utility operators to work with other stakeholders and identify and address interdependences and vulnerabilities to regional scale emergencies. A National Engineering Lifeline Committee, consisting of private companies, NGOs, and government agencies was also established in 1999. The regional engineering lifeline groups work closely with regional emergency management. (APEC, 2010).

**UK Natural Hazards Team:** Following the Pitt Review in the UK, the Natural Hazards Team (NHT) was set up in the Civil Contingencies Secretariat at the Cabinet Office. Its role is to establish a cross-sector resilience program between government, industry, and regulators. A Critical Infrastructure Resilience Programme has been established and, as part of this, government departments working on national infrastructure are working with NHT to develop Sector Resilience Plans. These form part of a wider National Resilience Plan for Critical Infrastructure. In spite of these efforts, the Institute for Civil Engineers and the Council for Science and Technology have said that this does not go far enough to establish a single point of authority with leadership to coordinate and mediate the responsibilities for infrastructure planning (Bissell, J., 2010).

**Regulations and procedures should facilitate the exchange of information between scientific experts and decision makers.** National policies and procedures should not hinder the incorporation of new scientific information into project design. This was perceived to be a barrier to incorporating revised design standards into new projects by the Inter-agency Performance Evaluation Task Force established after Hurricane Katrina (see Case Study 2).

**Establish a single point of authority** to coordinate work across different agencies (energy, communications, water, transport, environment etc.) and examine the risks and potential cascading failures across the whole infrastructure system, such as an infrastructure resilience council. This is also useful at the local or regional level (see Evidence 13).

**Coordinate DRM/resilience projects through the Ministry of Finance,** since they have direct access to and are the accounting office for all ministries.

Establish **national disaster management councils** and oblige public bodies and legal bodies that are involved in electricity, transport, finance etc. to participate and draft disaster risk-reduction operations and bear responsibilities for disaster risk-reduction activities in the event of a disaster (UNISDR, 2005).

## 5.1.2 Role of Economic Regulators

- **Regulators could revisit their regulatory frameworks and incentive and penalty structures so that they more accurately reflect the costs from service failures due to extreme weather events.** The regulator's mandate is to protect consumer interest and quality of service, which is negatively impacted when transport infrastructure fails due to exposure and vulnerability to natural hazards.
- **Coordination across regulators:** Economic regulators should coordinate to ensure that climate adaptation challenges are fully considered in the investment and maintenance plans of regulated utilities (PricewaterhouseCoopers, 2010; Cabinet Office, 2011).

### 5.1.3 Transport Planning

- **Transport priorities and performance-based metrics should include “resilience” and climate adaptation as separate criteria for appraising and evaluating projects (see Evidence 15).** Typically, transportation planning includes specific goals and objectives, which local authorities are expected to consider in their transport plans. These include public safety, economic competitiveness, a healthy environment, tackling climate change, and providing equal opportunities to all citizens. The “resilience” of transport infrastructure, however, is not often articulated as a goal in itself. In order for resilient transport projects to be constructed, this objective should be included in the department’s high-level strategic goals (for example, the Transport for London’s Sustainability Assessment Toolkit).
- **Procurement policies** could add filtering criteria to select those projects that have taken into account the risks from natural hazards, the longer-term risks from climate change, and those that have taken into account cross-sectoral adaptation. They regularly incorporate environmental criteria so could be expanded to consider adaptation (see Evidence 14).
- **Move away from a system of “how to move vehicles” towards “how to move people” and improve multi-modal transport.** Urban planning can be used to increase multi-modal transport, including non-motorized forms such as walking and cycling. This has the following benefits: (i) reduces traffic density and the need to build an increasingly large number of roads, which form obstacles to flood flow and exacerbate disasters; (ii) reduces the scale of the exposure and vulnerability of the transport sector (and the people and businesses that rely on them) to disasters; and (iii) provides resilient forms of transport in an emergency (walking and cycling) as well as provides resilience to other concerns, such as the volatile price of fossil fuel and climate change.

### 5.1.4 Local Approaches to Resilience

- Encourage **local approaches** to mitigate the effect of disasters on transport networks given the differential impact of disasters across a country and the presence of different microclimates across one stretch of a transportation network. Ensure that local authorities interact and share information on a regular

basis so that a similar level of resilience is met across regions.

#### EVIDENCE 13: Drain London

Drain London was launched following the GLA regional flood risk appraisal in 2006, which identified surface water flood risk as a “poorly understood and recorded type of flooding in London.” The responsibility had been spread out amongst numerous agencies and no organization had responsibility for coordinating the collaboration between parties and collating information.

Drain London seeks to establish ownership of London’s drainage assets, assess the condition of these assets, and secure a better understanding of the risk from surface-water flooding. Numerous stakeholders are involved in this consortium, including Transport for London, the Greater London Authority, London Councils, the Environment Agency, Thames Water Utilities, and London Development Agency. Whilst it was already the role of the City of London Corporation to forge partnerships with the adjacent LLFA and the Environment Agency as well as Thames Water, Network Rail, Transport for London, and the Highways Agency, Network Rail and the Highways Agency had not fully engaged in these partnerships. In light of this, it has been recommended that working arrangements should now be formalized in the form of Levels of Service Agreements or Memorandums of Understanding (Source: Drain London, 2011).

- Local authorities and communities should understand the risks affecting their infrastructure and what infrastructure is critical in their community. Workshops between local critical infrastructure representatives and asset owners to assess critical assets, interdependencies, service restoration time frames, and the impact of hazards on the local system, can provide invaluable information (Cabinet Office 2011). This information should be stored and used for future local planning assumptions and also shared with emergency responders so they understand where the priority infrastructure lies and how much time they have to respond before the infrastructure collapses.





resources against the criticality of that road. This helps prioritize roads for maintenance, upgrading, and decommissioning.

Salmonberry Bridge & Port of Tillamook Bay Railroad damaged during the Dec. 3, 2007, flood. Lower Nehalem River Road Confluence of the Salmonberry River & the Nehalem River, Salmonberry Oregon.

Chittenden County MPO in Vermont is working with the Department of Housing and Development to integrate climate change adaptation, hazard mitigation, and transportation into a single framework (Source: FHWA 2013).

**EVIDENCE 14: Auckland sustainable procurement process**

Auckland, for example, has included a sustainability principle in its procurement process to ensure sustainable outcomes and value for money over the whole lifetime of the goods, works or services under consideration. The procurement manual offers further information on tools that can be used, such as whole-of-life assessments or lifecycle approaches, which can take into account the total cost of ownership over the life of an asset (Auckland Council).

**EVIDENCE 15: Examples of Transportation**

**Plans, including Resilience**

The Boston Region MPO is one region that incorporates resilience into project selection, allocating points for projects that improve the ability to respond to extreme conditions (FHWA). It developed an interactive natural hazards mapping tool that links to the MPO's database of TIP projects and determines whether these are in areas exposed to flooding, storm surge or sea level rise.

The US Forest Service at Olympic National Forest has also evaluated ways to include climate change considerations into its Road Management Strategy, which is a tool that compares the risks that a particular road segment poses to various other

**5.1.5 Private Sector Infrastructure Owners and Operators**

Since the 1990s, the private sector's role in financing and operating public infrastructure has been growing. Through public-private partnerships (PPP), the private sector's contribution to all public infrastructure has averaged around USD 180 billion a year over the last few years (World Bank, 2014).

Through PPPs, the private sector can offer a number of advantages in terms of improving the quality of construction: namely, greater technical expertise and an understanding of lifecycle costing; efficiency and cost effectiveness; and the provision of resources, which are the most frequently cited reason for poor construction quality in developing countries. The disadvantages for developing countries are that the development, bidding, and ongoing costs in PPP projects are still likely to be greater than traditional procurement processes and the initial lead time for PPPs are costly, complex, and time consuming so need to be planned a long time in advance. PPP arrangements also require sophisticated regulatory and legal frameworks and the government must invest significant time and skilled resources during the development of PPPs as well as during the ongoing monitoring of the private sector. If the private sector is an owner/operator of transport infrastructure, the following actions should be taken:

- Infrastructure should be planned and designed taking into account the resilience approach high-lighted in Section 4;
- Business continuity plans should incorporate an understanding of the resilience of the operation and management of the infrastructure;
- These plans should be developed and reviewed with supply chain partners, service users, and emergency responders;
- Forums should be created for the private sector to share experiences, prepare business continuity plans, and provide training;
- Exchange and knowledge transfer information should be encouraged through business and trade forums.

### 5.1.6 Design Standards

- **Performance-based standards and systems analysis.** Consider implementing performance-based standards, which set the degree of functionality that infrastructure should reach within a defined recovery time, thus capturing the temporal dimension of resilience. Design standards are principally ensuring the robustness of the infrastructure in its environment, but not the integrity and reliability of the service that the infrastructure provides (Cabinet Office, 2011). Setting performance-based standards involves adopting a systems approach and assessing the criticality of infrastructure links within the network as well as understanding what the purpose of the assets/links are within the system (i.e. evacuation routes, links to hospitals, ports etc.). The potential failure scenarios for these critical infrastructure links can then be modelled in order to define an acceptable level of risk, which sets the time it should take for the assets to recover their functionality.

**Design standards must be continually reviewed to ensure that they are up to date, and the assumptions behind key metrics re-evaluated.**

This works best when designers/engineers push for new information on the basis of their first-hand experience designing and constructing infrastructure. Worse-case scenarios should also be explored to evaluate whether certain pieces of critical infrastructure should be designed for more severe weather events (see Evidence 16). Design standards should be reconsidered for the following:

- Subsurface conditions
- Materials specifications
- Cross-sections and standard dimensions
- Vertical clearance
- Drainage and erosion
- Structure
- Siting standards and guidelines

#### EVIDENCE 16: Examples of reviewed design standards

In Massachusetts, the state highway agency has updated its highway design manual based on the principles of context sensitive design so that transport projects are more in tune with the local context, include land use, and community and hazard considerations (Meyer, 2012).

Prior to Hurricane Katrina, state drainage manuals, AASHTO drainage guidance, and FHWA Floodplain regulations stipulated that bridges should be designed for a 50-year storm event, and the result was that state departments of transport designed for a riverine environment and did not consider the effect of wave actions on the bridge. Since then the FHWA has recommended a 100-year design frequency for critical structures that would consider a combination of wave and surge effects, as well as pressure scour when water overtops the structure. FHWA also suggested considering a 500-year design frequency (Meyer, 2008).

Since Hurricane Katrina bridges are being rebuilt with a higher clearance over the water as many bridge decks floated off their supports as the storm surged over the bridge (Meyer, 2008).

The Connecticut Department of Transportation, in a pilot project funded by the FHWA, is revisiting its hydraulic design standards for bridges and culverts, which reference rainfall data that has not been updated in decades. It will compare the hydraulic capacity using older rainfall data versus more recent data to evaluate whether design standards should be updated (FHWA, 2012).

The UK has increased its HD33 drainage standard and revised its pavement specification to use the French Enrobé à Module Élevé 2 (EME2) (Highways Agency, 2009).

The State of Maryland has issued guidelines





MEMA press conference on Hurricane Sandy.

that the “construction of new State structures, the reconstruction of substantially damaged State structures, and/or other new major infrastructure projects should be avoided, to the fullest extent practicable, within areas likely to be inundated by sea level rise within the next 50 years,” and “New State ‘critical or essential facilities’ shall not be located within Special Flood Hazard Areas designated under the National Flood Insurance Program (NFIP) and be protected from damage and loss of access as a result of the 500-year flood” (Johnson Z.P. [Ed.], 2013).

### 5.1.7 Project Identification, Preparation, and Appraisal Standards

**Governments can encourage disaster risk reduction to be mainstreamed into transport projects by issuing standards and guidance on project identification and preparation procedures. Resilience can be mainstreamed through the following means:**

- **Appraisal models**, which evaluate and prioritize the costs and benefits of various options, could also measure the cost of infrastructure damage, failure and service delays from multiple natural hazards, and the benefits of long-term resilience. Currently, appraisals assess the benefits of reduced congestion, improved reliability, low carbon emissions, increased mobility, and the costs of service downtime, strain on other services or the capital investment needed; though they do not explicitly include resilience.

- All **feasibility reports** should include an assessment of the impact of disasters on transport infrastructure.
- **Neighboring land-use practices and upper catchment land management should be included within the scope of transport projects.** Improving the resilience of transport infrastructure begins first and foremost by examining and improving adjacent or upper catchment land use. Ultimately, low-cost solutions, such as strategic reforestation of upstream agricultural land, are significantly more cost-effective than raising the height of a bridge and investing resources in increased scour protection (see Case Study 7 and Evidence 17).
- **EIAs can become critical tools for mainstreaming resilience into transport infrastructure by explicitly addressing the impact of natural hazards on infrastructure, and also by taking climate change into consideration and how a project will respond to an “evolving environmental baseline” (EC 2013b: 15).** EIAs in many developing countries, however, are often absent or disconnected from the analysis and design process. This is mainly as a result of financial and political pressures, which prioritize maximizing the length of the road network. Politically, roads are a massive vote puller. In Nepal, for example, the arrival of bulldozers gave

voters “instant roads,” yet this caused massive environmental damage and also increased the sediment load in mill hill rivers, exacerbating flooding throughout the system (see Evidence 18).

- **Project reporting standards:** Technical experts must ensure that there are project evaluation and reporting requirements in place to share all information about the project’s capabilities and limitations with key decision makers and emergency responders. Emergency responders particularly need to be informed of the dangers of collapse and the “time of failure” (Englot and Zoli, 2007).
- **Standards can stipulate the study teams and stakeholders to be engaged in the identification and planning of all transport projects in order to ensure the impact of natural hazards is taken into account.** These could include: transportation planners, GIS specialists, asset managers, climatologists and seismic experts, climate change research centers, maintenance personnel, design engineers, environment agency personnel, and local communities.
- Guidelines should prescribe engaging with communities and emergency responders right from the initial project design through to identifying and evaluating adaptation options. They have first-hand knowledge of the local system, which is invaluable for gathering information on the consequences of extreme weather events on transportation infrastructure. By involving the community in the decision-making process, the project is more likely to be well designed and maintained. See Evidence 19 for examples of how a lack of real and effective engagement with the public has posed critical challenges to the construction of resilient infrastructure.

#### **EVIDENCE 17: Upper catchment land management**

The importance of land-use practices is highlighted in a case study report, “*Making Informed Adaptation Choices: A Case Study of Climate Proofing Road*

*Infrastructure in the Solomon Islands*” (2011), which analyzed the Solomon Islands Roads Improvement Project (specifically, sub-project 2) following the 2009 floods. This project was funded by the Asian Development Bank and the governments of Australia and New Zealand. The report found that engineering approaches and solutions were the primary focus of risk-reduction measures and whilst non-engineering climate adaptation strategies, such as better upper catchment land management, including minimizing impacts of commercial logging practises (which had led to major landslides and debris trapped at bridge sites), and deforestation, were noted, they were not pursued as they were considered to be beyond the scope of the project. Also, whilst the instability of the soft alluvial soils was noted, it was decided not to significantly realign the existing road because of particular concerns about land tenure issues (Narsey Lal and Thurairajah, 2011:10).

#### **EVIDENCE 18: Natural hazards and EIAs**

The European Investment Bank has included in its Environmental and Social Statement and Handbook requirements that projects apply cost-effective, appropriate adaptation measures where there is a risk from climate change, and more extreme weather events. The EIB will only finance projects that fulfil these requirements.

DFID and the European Bank for Reconstruction and Development have also developed a toolkit in 2010, which included guidelines on integrating risk assessment and adaptation into project feasibility studies, environmental and social impact assessments, environmental actions plans, and water audits (Acclimatise and Cowi, 2012).

In Japan, permission for highways and bridges is first obtained from DRM organizations (Ishiwatari and Sagara, 2012). The Caribbean Development Bank (CDB) has also developed guidelines for natural hazard impact assessment (NHIA) and their integration into EIAs (CDB and CARICOM, 2014).



Flooding and damage to Metro-North's system—in the aftermath of Hurricane Sandy—to the bridge and south yard at Harmon.

#### **EVIDENCE 19: Public perception issues in construction**

A rural access project in Trinidad and Tobago involved investigating and making recommendations on the feasibility of rehabilitating and upgrading a substantial number of roads on the island. As it was year three of the program, the economics of a positive EIRR for the roads was low to negative so an acceptable engineering solution was for the use of double-bound surface treatment (DBST), effectively two layers of surface dressing, for the low traffic volume. The Trinidad Road Authority, however, refused to countenance this option as members of the public had previously commented that unless hot-rolled asphalt (HRA) was used they did not consider it a “proper” road. The cost and difficulty of laying HRA surfacing material on often tortuous and hilly alignments had unexpected detrimental effects on the road drainage layout and caused a large number of small to medium landslips on a supposedly stable road alignment, which would not have been caused by the use of DBST (Source: IMC Worldwide interview).

A three-year rolling program of road rehabilitation works and repairs in Trinidad to address landslips arising from the shallow internal angle of friction of the over-consolidated clays adjacent to the numerous ridge roads faced a number of problems due to poor communication between the authorities and the public. An economic and structurally appropriate engineering solution had been adopted, but issues with detailing led to a large failure rate by year three of the program—there was poor drainage to the back and foundation of the gabion retaining

walls, which was exacerbated by the fact that the gabion height was below ground level, causing rotational failure of the entire wall. The client was not interested in modifying the details of the design due to perceived issues with public perception and loss of face (Source: IMC Worldwide interview).

#### **5.1.8 Information—Generation, Collection, Exchange, and Dissemination**

- **Improve and revisit on a regular basis the collection of data on natural hazards and the modelling and analysis of this data.** For flooding this can include: reducing the time lag between data collection and analysis to the receipt of data on a daily basis; improved flood modelling and analysis; rehabilitation of radar and improvement of the hydromet systems to allow for better utilization of upstream hydrological information; and to provide predictions of flood levels, flows, peak travelling speed, and potential inundated areas (World Bank, 2010). It is also particularly important to continually revisit flood maps as climate change has resulted in higher than expected flooding levels (see Evidence 20).

#### **EVIDENCE 20: Flood maps and Hurricane Sandy**

Unexpected levels of flooding during Hurricane Sandy meant that efforts to pre-emptively relocate rail equipment to higher ground on the basis of past flooding and historical experience was ineffective as



existing flood maps were no longer accurate (Lau and Scott, 2013: 94).

- **Standard formats and reporting standards should be introduced for monitoring and collecting damage data (see Case Study 4).** Standardized data can be used as a default standard for designers (rainfall intensity charts, IDF curves). In many developing countries, the choice of data is left to the discretion of the consultants, and particularly smaller budget projects will not commission hydrological studies (World Bank, 2010).
- **A timetable of regular risk assessments and audits** for infrastructure assets can provide information on their condition and reliability.
- **Knowledge sharing should be improved between transportation agencies, climatologists, scientists, insurance companies, and those professionals and volunteers on the frontline of emergencies.** Open sharing of information deepens the understanding of risks and solutions but operators are normally unwilling to let others free ride on information they have invested and which may be commercially sensitive. This information could instead be provided to an independent third party that could sanitize the information and the data could be “sold rather than provided for free” (PricewaterhouseCoopers, 2010). See Evidence 21 for examples of information sharing between insurance companies and governments.

#### **EVIDENCE 21: Insurance companies and data sharing**

RMS, a leading catastrophe risk management firm, has announced that governments will have free access to its catastrophe models to dynamically analyze risk and develop appropriate risk-mitigation decisions. This is a public-private partnership with UNISDR and the World Bank (RMS, 2014). The Insurance Council of Australia has also entered into a memorandum of understanding with Queensland to share its data, which has been combined with government-held geospatial data to produce an interactive online tool that allows the public to see which locations have been affected by disasters (Barnes, P., et al., 2014).

When cross-border issues and international treaties lie at the heart of a systems failure there needs to be improved inter-agency coordination and information-sharing across regions, and mechanisms for conflict

resolution. Transport infrastructure often crosses borders and therefore regional cooperation and sharing of information amongst forecasters, decision makers and climate information users are essential components, particularly because of the trans-boundary nature of many disasters. In the case of Kosi, Nepali contractors were awarded maintenance work within Nepal, but the ownership and direction still lay with India. Failures in effective maintenance work were not picked up in time, and the upstream embankment was breached (see Case Study 1 and Evidence 22).

#### **EVIDENCE 22: Mozambique regional exchange of information**

In recognition of the trans-boundary nature of Mozambique’s rivers, national flood forecasting is supported by the Southern African Regional Climate Outlook Forum (SARCOF). The SARCOF facilitates the exchange of information amongst forecasters, decision makers, and climate information users in the 14 SADC member states. This forum meets each September to prepare a seasonal forecast for the SADC countries. The water authorities also exchange data on a regular basis. It is reported that such information sharing can transcend political disagreements—with Mozambique and South Africa reported to remain in communication during the 1980s when the countries were close to war (Hellmuth, M. et al., 2007).

- **Infrastructure companies should be encouraged to disclose information on how they have taken the risks from natural hazards into account.** Information disclosure is a useful tool for generating market pressure and incentivizing behavior change. Stakeholders can scrutinize this information, identify cross-sectoral adaptation measures, and create pressure for infrastructure owners/operators to adopt best practice (PricewaterhouseCoopers, 2010).
- **Keep records of past weather events and create harmonized data-sharing mechanisms** through a national GIS system, for example (see Evidence 23). Use this to review return periods of storms and flooding events in light of new information and in turn revise design parameters

and recommendations.

### **EVIDENCE 23: GIS and crowd-sourcing maps**

Following the 2010 earthquake in Haiti, maps were produced by more than 600 volunteers from the OpenStreetMap community who used high-resolution imagery made available by the World Bank, Google, and others, and digitized the imagery to create a detailed map of Port-au-Prince. Volunteers from 29 countries made 1.2 million edits to the map, and condensed a year's worth of cartographic work into 20 days. The World Bank has since used OpenStreetMap to create maps of the built and natural environment in more than 10 countries (WEF, 2014).

**Infrastructure sectors should engage in weather information collection specific to their sector as weather has specific and varied local impacts on transport infrastructure.** Information generated by the central meteorological center is often too generic for specific types of infrastructure or sectors. Infrastructure sectors should deepen their understanding of weather impacts and collaborate on information gathering. For example, the effect of weather on overhead lines will affect the railway sector.

## **5.2 Financial Arrangements and Incentives**

Financial arrangements are needed that encourage coordination across infrastructure sectors, promote a coherent long-term vision, the incorporation of resilient criteria in infrastructure projects, and long-term planning for disaster risk management. Measures that promote resilience, for example increasing redundancy, will also increase immediate costs even if in the long run these measures prove to be cost-effective. Therefore, financial incentives and penalties are needed to promote resilience.

### **5.2.1 Emergency Funds and Insurance**

Pre-emptive disaster planning can include setting aside emergency DRM funds or transferring risk to sovereign insurance pools. Emergency funds could be contingent upon departmental prevention and mitigation plans (see Evidence 24). A number of reports (see Case Study 3) and interviews conducted for this report noted that poor budget discipline and a reliance on aid took the onus away from governments to provide strategic leadership and take proactive measures to increase the resilience

of transport infrastructure.

For further discussion on regional insurance funds see Section 7 on emergency response and risk reduction.





Bridge damage from the 1989 Loma Prieta earthquake in California.

#### EVIDENCE 24: African Risk Capacity

African Risk Capacity (ARC) is a regional insurance pool in Africa, which provides payouts to governments contingent on the establishment of appropriate contingency plans and early warning systems that are evaluated by ARC's Board Peer Review Mechanism. This is a move from the old "response" paradigm towards pre-disaster risk management.

### 5.2.2 Cost-Sharing Mechanisms

**Innovative approaches to financing cross-sector adaptation should be encouraged, including cost-sharing mechanisms that share the responsibility for measures that offer co-benefits and address the free rider problem.** Natural hazards can be turned into disasters by the actions of certain agencies (agriculture, planning, transport etc.) that do not consider the impact that their practices have on raising the hazard exposure and vulnerability on neighboring sectors. The impact of modern farming practices on downstream flooding (see UK flooding Case Study 7) has now been accepted in many countries, yet it is a challenge to either incentivize or enforce changes to these farming practices. Similarly, the power sector is vital for the operation of the railway, yet it is the power sector that bears the costs of adaptation.

#### EVIDENCE 25: Cost-sharing mechanisms in Japan

In Japan, for example, cost-sharing mechanisms exist between public works organizations and DRM organizations to share the cost of raising the height of expressways (Ishiwatari and Sagara, 2012). Roads built on higher ground can provide routes for evacuation and embankments can provide evacuation shelters for nearby residents. Roadside service stations, service stations, and parking areas along highways can serve as bases of operation for rescue teams and evacuation shelters for nearby residents (Ishiwatari and Sagara, 2012).

### 5.2.3 Infrastructure Banks

**An infrastructure bank can offer a coherent and consistent vision on resilient infrastructure, which bypasses the problem of political and industrial short-termism and the fragmented nature of some infrastructure projects.** It can also tap new sources of private funding (Jones and Llewellyn 2013). An infrastructure bank would be an entity to assess infrastructure projects across agencies and authorities and develop objective and uniform criteria, particularly related to resilience, to select and prioritize projects. Such a bank would bring together experts from transportation, energy, environmental resources, and

emergency response and coordinate work across modes, sectors, and regions. It would also serve as a knowledge hub to disseminate information on vulnerabilities, solutions and best practices (NYS 2100 Commission, 2013). Through this bank, infrastructure planning could have a more systemic approach that would enable more strategic and, perhaps, resilient investments. An infrastructure bank can encourage private sector investment by either providing a partial or full guarantee to support the initial equity cost of the project's finance, or the repayment of bonds issued directly by investment projects. It does not directly distribute public money, but rather, raises funds for lending by issuing national investment bonds, for example. These can be attractive investment schemes for pension schemes and insurance companies (see Evidence 26).

#### **EVIDENCE 26: South Carolina Transportation Infrastructure Bank**

The South Carolina Transportation Infrastructure Bank (SCTIB), for example, is one of the most active infrastructure banks in the U.S. established by the 1995 National Highway System Designation Act, and has invested nearly USD 2.8 billion. It provided USD 66 billion to the SCTIB, which supports highway and bridge projects exceeding USD 100 million and transit projects. The SCTIB helps accelerate across the state the timeline of 200 transportation projects from 27 years to seven years (NYS 2100 Commission, 2013: 164).

### **5.2.4 Resilience Auditing and Resilient Selection Criteria**

**Resilience selection criteria such as the USA Tiger Discretionary grants (see Evidence 27) and resilience auditing can encourage decision makers to incorporate resilient investment criteria into transport infrastructure.** For example, the Institute for Business and Home Safety (IBHS) is a consortium of insurance companies in the U.S. seeking to improve the resilience of infrastructure by offering a fortified for Safer Living designation (FFSL), which is similar to LEED (Leadership in Energy and Environmental Design). It is anticipated that this certification will help secure tax credits and lower insurance premium. IBHS expects that this program will extend across all critical infrastructure facilities, including transport.

#### **EVIDENCE 27: US TIGER Discretionary Grants and Resilient Selection Criteria**

In the US, TIGER Discretionary Grants are awarded based on primary and secondary selection criteria. One of the primary selection criteria is “improving the condition of existing transportation facilities and systems, with particular emphasis on projects that minimize life cycle cost and improve resilience” (DOT, 2014: 12). The Department of Transportation assesses whether and to what extent:

“(i) the project is consistent with relevant plans to maintain transportation facilities or systems in a state of good repair and address current and projected vulnerabilities; (ii) if left unimproved, the poor condition of the asset will threaten future transportation network efficiency, mobility of goods or accessibility and mobility of people, or economic growth; (iii) the project is appropriately capitalized up front and uses asset management approaches that optimize its long-term cost structure; (iv) a sustainable source of revenue is available for operations and maintenance of the project; and (v) the project improves the transportation asset's ability to withstand probable occurrence or recurrence of an emergency or major disaster or other impacts of climate change. Additional consideration will be given to the project's contribution to improvement in the overall reliability of a multimodal transportation system that serves all users” (DOT, 2014:12).

## **5.3 Expertise**

### **5.3.1 Capacity Building for Officials and Civil Servants**

**Tools, education, training material, and exercise programs are needed so that government officials and civil servants understand the principles of resilience in transport and can carry out assessments, use revised project screening and monitoring tools, and develop action plans.** The bureaucratic system's inertia and inadequate capacity with respect to prompting organizational change pose a challenge to implementing Disaster Risk Management in the transport sector. Many national strategies already recognize the need for the identification of flood-prone areas, adaptation of building codes, and plans for construction. However, more projects are needed that can help with the change process. Core areas of training are particularly needed in (World Bank draft):



Earthquake-damaged road between Port-au-Prince and Léogâne has failed, but is still in a functioning state. It is now at risk of complete failure during rainy season as the subgrade is exposed.

- Spatial planning
- Risk analysis
- Knowledge of mitigation strategies and protective measures
- Partnership building and networking
- Collecting, storing, and sharing information
- Program evaluation, management, and design expertise

### 5.3.2 Widening Expertise

There is a need for more experts who understand the role of DRM in infrastructure on project management teams, including hydrologists, and climate and DRM specialists. A national advisory body or a pool or database of experts could provide the necessary expertise and broaden the perspectives included in project teams (ADPC, 2014).

### 5.3.3 Engineering Skills Base

**Improve the development skills base among engineering consultants, as well as management supervision skills.** Engineers need to be trained to adopt a systems perspective during the design and planning of infrastructure. This could be done through working closely with universities or including further professional registration requirements. Well-qualified consultants must be selected for engineering design studies and works supervision, following the observation

in a number of case studies that some damage had resulted from poor design or poor construction techniques.

### 5.3.4 Communities

**Increasing awareness and learning in communities around hazard-affected areas can help provide early detection of problems and inefficiencies, as well as increase their ownership of the operations and maintenance of the infrastructure.** Communities can be taught early warning signs, such as tension cracks opening in the ground high above the road bench, minor rock falls, and slips at the foot or edges of the potential slip areas. Infrastructure development is also more successful and sustainable when roads are maintained and built using community labor-based methods. It builds the skills of local communities and the capacity for replication, operation, and maintenance of works. It also provides more opportunities for salvaging and reusing existing materials after a disaster.

#### **EVIDENCE 28: Community labor-based methods in Afghanistan**

The village of Jabraeel on the banks of the Harirud River in Herat province has repeatedly suffered from flooding as the water overflows the river's natural banks. The flooding has been exacerbated by unpredictable weather, the mismanagement of natural resources, and the construction of infrastructure that has encroached on the natural riverbed. Women in the community were trained to



build gabion baskets (cages weaved from wire) and men filled them with stones, ensuring full community participation in the process. The gabions were then used to build a wall that would reduce the damage caused by flooding to the community (UNOPS, 2012).

## 5.4 Technical–Planning and Design

### 5.4.1 Introduction

Resilient infrastructure requires commitment to mainstream resilience at all stages of the project cycle. It requires high-level strategic priority to ensure adoption of the principles of resilience in project implementation and infrastructure design and construction. The planning and design stage can: (1) mitigate its vulnerability and exposure to natural hazards; (2) minimize the severity of the consequences when damage or failure does occur;

and (3) aid recovery of affected communities by identifying and strengthening disaster management planning and procurement of funds (see Evidence 29).

Technical planning and design measures are implemented through building the enabling environment for resilient infrastructure through projects aimed at strengthening institutions, capacity building, construction

supervision, operations and maintenance, and finance. The implementation and success of technical planning and design measures are determined by institutional measures, which range from new operations and processes, to new regulations and standards through to significant policy and institutional changes. Technical measures may also demand different levels of capacity building to be implemented, ranging from simple training programs to more complicated awareness-building activities aimed at mainstreaming new approaches or ways of thinking. These technical measures in turn entail various financial implications.

A series of technical measures have been developed that represent the issues that should be considered for various infrastructure assets in relation to potential risks. The measures have been tabulated and ranked against the resilience domains using a simple traffic-light system. The ranking of each measure was derived from discussions with infrastructure experts and therefore represent engineering judgment. As such, it is open to variation in opinion and should be used only as a guide.

The tables are designed to support the project designer in assessing the risks to infrastructure and to aid in prioritizing interventions to maximize value for money in interventions. The rankings allow the project designer to consider each measure against the domain in which it can be implemented and the difficulty of achieving a successful outcome in that domain.

IMPLICATIONS	TRAFFIC-LIGHT SYSTEM		
POLICIES, INSTITUTIONS, AND PROCESSES	OPERATIONAL	REGULATIONS/ STANDARDS	INSTITUTIONAL/POLICY CHANGES
CAPACITY BUILDING	SIMPLE TRAINING	INTERMEDIATE	NEW APPROACH/WAY OF THINKING
FINANCE/COST	NO/LIMITED COST IMPLICATION	MEDIUM	HIGH
OPERATIONS AND MAINTENANCE	ROUTINE	INTERMEDIATE	SIGNIFICANT CHANGE
TECHNICAL SOLUTIONS	SIMPLE	INTERMEDIATE	HIGH TECH/COMPLEX
	EASY		HARD

Table 1: Technical measures and resilience domains

Two tables providing examples of the technical measures, which can be deployed to mitigate the risks to linear infrastructure and bridges from earthquakes, are included below. For further technical measures for various infrastructure systems see the Annex, which sets out the range of failure scenarios all infrastructure experiences under each hazard event—flooding, earthquakes, landslides, hurricanes/cyclones, tsunamis, extreme heat, extreme cold, wildfires and mudflows—and provides technical assessment sheet for each infrastructure mode.

**EVIDENCE 29: Designing for emergency, evacuation, and recovery effort**

In a major recovery effort, the logistical vehicles from overseas aiding the effort will need to be accommodated within the local transport and logistical networks. Thought must be given as to how best to use low-speed vehicles such as agricultural tractors with trailers that have exceptionally high ground clearance and can work in deep water or mud

during the initial period where existing roads have been destroyed and conventional vehicles cannot work. Critical links should therefore be designed and engineered to accommodate both the heavy vehicle and axle loads, and the size of the vehicles required to aid the recovery efforts. The structure of the pavements must also be strong enough to carry the loads without failures that will hinder the aid effort. An axle load of 20 tonnes is suggested against the more standard 11.5 tonnes per axle on routes of key importance. In addition, the road's width and alignment must avoid "pinch points" that will restrict exceptionally wide or long loads that may need to be imported into the damaged area. Bridges must also be able to resist the anticipated event and remain able to carry exceptionally heavy loads imposed by construction equipment.

### 5.4.2 Earthquakes

Table 2 illustrates the failure scenarios associated with earthquakes for all transport infrastructure. (Failure scenario tables for other hazards are found in the Annex, Section 8.5).



<p><b>Liquefaction</b></p>	<p>(i) Liquefied soil forces its way to the surface, breaking through <b>roads, railways and runways</b>, causing uplift, subsidence, and voids. This uplift of the transport structure also damages underground infrastructure <b>drainage</b> and surface drainage systems, as well as services such as <b>utilities, tanks, pipes, and manholes</b>.</p> <p>(ii) On slopes, the ground “slides” on the liquefied layer. Cracks and fissures can occur at the extremities of the slide.</p> <p>(iii) Uplift damages <b>underground infrastructure services</b> such as utilities, tanks, pipes, and manholes.</p> <p>(iv) Contamination of the materials in the <b>road</b> from the liquefied soil.</p> <p>(v) Lateral spreading from liquefaction can apply pressure to <b>bridge</b> abutments, reducing bearing capacity or the integrity of the structure. It also applies pressure to <b>quays and seawalls</b>, reducing their bearing capacity and the integrity of the structure. Many <b>ports’</b> facilities are constructed on fill materials placed over historic wetland. Such materials are generally fine and granular in nature and susceptible to liquefaction if provisions are not made to resist such force or relieve the pore pressure resulting from higher water table and seismic shaking.</p>
<p><b>Structural failure</b></p>	<p>(i) Surface and sub-surface water <b>drainage</b> system failure.</p> <p>(ii) Failure of <b>utility and traffic-control</b> systems.</p> <p>(iii) Major/severe cracks that have the following effects: damage to the <b>carriageway</b> surface; disorientation of <b>railway</b> track and track buckling; shear failure of <b>pier, abutment, deck, and surface</b>; the <b>tunnel</b> lining leading to damage/collapse.</p> <p>(iv) Damages to <b>structures</b> such as storage buildings, paved storage area, storage tanks/cranes/heavy equipment/shipping containers/heavy cargo, runways, taxiways, control towers, radar systems, fuel facilities, and supply facilities due to ground movement/shaking.</p>
<p><b>Land / Mudslides</b></p>	<p>Refer to the failure scenarios and approaches under section on landslides.</p>
<p><b>Tsunami / Wave / High Tide</b></p>	<p>Refer to the failure scenarios and approaches under section on road/railways under the sub-section on tsunami/extreme low pressure (wave/high tide).</p>
<p><b>Flooding</b></p>	<p>Refer to the failure scenarios and approaches under section on bridges/tunnel under the subsection on flooding.</p>

Table 2: Earthquake failure scenarios

### 5.4.3 Linear Infrastructure (Roads and Railways) Measures: Earthquake

Key measures to reduce the risk of earthquakes highlight the importance of ground investigations and quality control of not just the infrastructure itself but sub-soils beneath a road or railway and the materials used for embankments. The importance of adequate drainage detailing is also highlighted. Most measures listed increase robustness of the infrastructure, the exception being the choice of whether to opt for earth or gravel, flexible (asphalt) or rigid (concrete) pavement construction—which is a choice between designing for

safe failure or increased robustness. The trade-off is not just reflected in the contrasted cost-benefit analysis between capital expenditure and maintenance, but the speed and methods required to reinstate the infrastructure in the case of an extreme event—a flexible structure will fail quicker but the robust solution may not be able to be reinstated as easily if it fails.

A structure designed for “safe failure” will also have been designed to limit cascading failures within the system and will therefore limit the overall extent and costliness of the damage.

	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Identify and seismically improve critical access links (for example, as achieved in the case study on the Great East Japan Earthquake).	●	●	●	●	●
<b>PREPARATION AND DESIGN</b>					
Choose pavement type to reduce initial damage and reduce time for repair works and fill damaged areas prior to ingress of water can be detrimental in the case of further aftershocks (e.g. <b>earth and gravel construction</b> for rural roads, bituminous <b>flexible as opposed to rigid concrete pavements</b> in some cases). This is an example of <b>safe failure</b> .	●	●	●	●	●
Design <b>seismically reinforced embankments</b> , particularly on critical sections of access routes. This could be achieved by protecting embankments with RC walls or RC in-situ slabs on side slopes/toes, and to details which avoid weakness at joints.	●	●	●	●	●
<b>IMPLEMENTATION</b>					
Consider the use of <b>flexible below ground services pipes</b> (plastic rather than steel or concrete).	●	●	●	●	●
Ensure all <b>buried pipe drainage makes provisions for earthquakes</b> (e.g. By using short length concrete spun pipes, flexible joints, short pipe connections into manholes and manholes with liquefaction/seismic design criteria).	●	●	●	●	●
Separate pavements/railway track beds from underlying materials to <b>prevent contamination where liquefaction is a potential problem</b> (e.g. filter layers or filter fabrics).	●	●	●	●	●
For critical access routes <b>replace weak and soft soils</b> below embankments/pavements or strengthen using piles or stone columns to take foundation down to a sound bearing material.	●	●	●	●	●

Table 3: Linear infrastructure and earthquakes

#### 5.4.4 Bridge Measures: Earthquakes

These measures focus on the design of the bridge structure and foundation, either through increasing robustness or designing some elements to be stronger and allowing safe failure of parts of the bridge to preserve the critical load-bearing elements of the bridge structures. The example of pinned articulations in suspension bridges highlights how robustness can be increased through providing greater redundancy within the transport infrastructure design itself.

#### 5.4.5 Conclusions

In general, resilience is shown to be increased either by: (i) designing the infrastructure itself to be more robust; (ii) designing for safe failure or flexibility; (iii) increasing the robustness of protection works; or (iv) separating the infrastructure from the risk or hazard. Many of the measures identified increased **robustness** by mitigating the hazard and reducing the exposure and vulnerability of the infrastructure. Airports, for example, are generally provided as fairly robust infrastructure with much more robust pavements than roads due to heavier impact loads, and thereby substantial resistance to extreme events already present in designs. Robustness also includes measures that increase resilience of other infrastructure that is interdependent on transport such as power cables, ITC, fuel supply, and water infrastructure. In contrast, **redundancy** and **safe failure** (see Evidence 30) are measures that accept the risk but limit wider catastrophic failure within the system, thus increasing overall system robustness. **Flexibility** is about including the potential to increase future robustness by, for example, allowing the flexibility to raise bridge decks to accommodate increased water levels in the future.

Measures that increase robustness are not limited to those that increase the strength of the infrastructure itself (either substructure or superstructure), but also increased robustness of associated measures or protection works to mitigate against hazards. Infrastructure protection can be enhanced by stabilizing slopes and scour protection, or risks mitigated through upstream river training works, reforestation, sustainable urban drainage systems (SUDS) or the introduction of buffers in the system (floodplains). In many cases these

measures, which increase robustness of the overall transport system rather than the infrastructure itself, can be more cost effective.

#### EVIDENCE 30: Safe failure of timber jetties in Bahamas

Hurricane Floyd swept through the Bahamas in 1999 and destroyed a number of timber jetties as a consequence of the waves either surging up underneath and popping the planks into the air, or imparting vertical uplift loads to the piles causing them to be loosened or lifted from the seabed. Rather than adopt a heavier construction or different materials, an alternative approach was utilized whereby the timber decking was designed as drop in removable panels.

These were designed to break away at the point where the force of the waves on the panels risked transmitting this impact to the surrounding structure. This is a good example of designing for “safe failure.” See Case Study 17 for more details.

## 5.5 Operations and Maintenance

### 5.5.1 Maintenance

Maintenance is required to maintain the condition of transport infrastructure, yet most countries continue to prioritize the construction of new roads over upkeep of the existing network. Maintenance works are needed for culverts; canals; removal of sedimentation; control of vegetation; slopes; and repair of edge; shoulders; potholes; and cracks. The economic case for maintenance is significant, and is only a small fraction of the construction cost—5 percent to 6 percent per annum for an unpaved rural road (Neal 2012). In reality, however, only 20 percent of Asian rural roads have consistent, regular, and routine maintenance whilst 80 percent is spent on emergency unplanned repairs and reconstruction activities. A similar pattern is found in sub-Saharan Africa.

Maintenance can be optimized through:

- Adopting performance contracts for routine maintenance tasks;
- Effectively using local resources, particularly human resources, locally appropriate materials, and locally

available and low-cost equipment;

- A nationally coordinated program with consistent standards and an ongoing program of training, retraining;
- A maintenance program that requires little planning, supervision, and the need for highly qualified technical staff;
- Equipping maintenance crews with non-destructive

### 5.5.2 Transportation Asset Management (TAM)

TAM is a move from a reactive to preventative maintenance approach, and it can also provide an effective platform for keeping a record of infrastructure damage and helping government agencies understand where to prioritize investment across the transport network as it tracks an asset's entire lifecycle. Whilst most TAM goals look at reliability, performance, and efficiency they do not currently detail the specific causes of failure, such as extreme weather (Meyer et al., 2012). Any hazard that affects the condition, performance, and life of the asset and its ability to provide a reliable and safe service will influence the timing of rehabilitation and replacement (Meyer et al., 2012). If a TAM goal was to increase resilience to high-consequence events in a cost-effective manner, then this would in turn inform the development of objectives, performance metrics, and data-collection efforts to help manage extreme risk. Assets that are repeatedly affected by weather events could be flagged (the flag could come from maintenance asset performance logs, maintenance work orders, road condition) and the costs of those events tracked. Risk ratings or vulnerability indicators can also be included in an asset-management database to enable agencies to quickly see where to target adaptation actions. Further information could be gathered by on-site investigations, historical records, topographical surveys, and interviews with local people living nearby.

### 5.5.3 Inspection

Regular and detailed inspection is required to underpin maintenance and assess whether specific repair works are needed. In some cases, such as for bridge bearings of major structures, inspection and maintenance requires specialist access skills. Bridge inspections

testing and sensing devices to locate and analyze problems;

- Mobilizing pre-established repair units and equipment to efficiently treat minor deficiencies;
- Improving the interface between utilities and transport infrastructure to minimize asset damage due to utilities access and repairs.

should include load-control testing and the rehabilitation and replacement of key components such as bearings to ensure infrastructure remains safe. Although bearings are a vital part in ensuring service continuity and the safety of bridges, they can be dangerously and easily overlooked by cash-strapped asset owners and managers, particularly for aging infrastructure where there has been a lack of ongoing maintenance (NCE Editor, 2014).

### 5.5.4 Real-time Monitoring

Real-time monitoring allows the collection of "live data" of structures, often bridges, and is particularly useful as the science of flood forecasting still has a large degree of uncertainty and is currently available at too large a spatial scale to inform effective mitigation measures (Benn, J., 2013).

Data is generally collected through pre-placed sensors, which feed into a remote monitoring system that can be used to analyze and report data. Monitoring of data allows real-time decisions to be made affecting the operation, maintenance, and safety of bridges. Real-time monitoring systems have been successfully used in bridges as part of their operational requirements, particularly on major or long-span bridges, which require constant monitoring, often in regard to environmental or weather conditions. Bridge monitoring technology exists. It allows the long-term monitoring of settlements of new construction, effects of locked bearings, subsurface erosions, and settlement of bridge supports (TRB, 2010). Relatively recent developments include the improvement of measuring long-term motions and vertical displacements at bridge piers and abutments of settlements, scour, and subsurface erosion. Many of these developments have been possible due to the falling cost of sensor technology. The community can

also play an important role in monitoring potential hazards (See Evidence 31).

**EVIDENCE 31: Community landslide early-warning system in Sri Lanka**

A community-based landslide early-warning system was implemented in Sri Lanka. It involved the community in capacity building through participation in hazard mapping, identification of safe areas, and participation in mock drills. These community aspects were done in conjunction with rainfall monitoring systems using a dynamic computer model to allow early predictions of landslide areas. The community also identified improvements to the emergency procedure by identifying problems with evacuation routes (ADRC, 2008). The relatively recent developments of the Internet and mobile phones all offer new communications mechanisms to better support more holistic approaches to DRM and communication in transport (National Research Council, 2006) (UNISDR, 2009).





Runway snow removal at Atlanta airport.

## 6. EMERGENCY RESPONSE AND RISK REDUCTION

### 6.1 Introduction

The period during and immediately after a disaster, lasting up to two months, involves evacuating residents, restoring critical lifeline routes, and basic access and mobility as well as patching damaged infrastructure. This is the interim period before the reconstruction process can begin and pre-disaster levels of function are restored. Emergency management consists of relief and some rehabilitation. A resilient transport system is one that is able to function even when infrastructure is damaged or destroyed, and can restore a full level of service within a specified timeframe.

This chapter includes a discussion of the plans and assessments that must be arranged before a disaster strikes in order to allow the affected country's government to rapidly deploy the necessary equipment, personnel, transitional traffic measures, etc. and resume

functionality as quickly as possible. If this process is managed smoothly, a space can be created for the government to simultaneously begin assessing the damage and considering how to “build back better” (See Section 7).

It also offers some examples of practical ideas, which professionals can promote through Technical Assistance Projects to encourage emergency risk response in the transport sector:

### 6.2 Policies, Institutions, and Processes

#### 6.2.1 Prioritize and Categorize Lifeline Routes

Transportation lifeline networks, which are essential to regional and national mobility, should be identified and prioritized. These are routes that would aid in

evacuations and maintaining basic transportation services. Identify and categorize this lifeline network through a risk-assessment process based on criteria determined by stakeholders and a consideration of economic, environmental, and social impacts. The categorization of networks and the approximate timeframe for services to be restored can be set through performance-based standards.

- **Lifeline audits** should be conducted to assess performance during both expected and extreme disaster scenarios to help with response planning (SPUR, 2012).
- Consider critical infrastructure, such as power and water, which particularly need to be well networked and accessible for the emergency services and more generally for the public, during and immediately after a disaster.
- Consider the interdependencies between transport modes. For example, port operators need to liaise with rail and road operators linking to and from the ports.
- Communicate this categorization in advance to the general public, agencies, utilities and emergency service providers. This will help manage public expectations and improve mobility after a disaster. It will also ensure transportation agencies identify what investments are needed to maintain these transportation lifeline networks.

#### **EVIDENCE 32: London Resilience Road Network**

The London Road Resilience Network identifies the roads in Greater London that need to be kept open in times of extreme weather to allow essential services to operate reliably and safely. It also ensures continuity across jurisdictional boundaries for the entire transport system (Department for Transport 2014).

### **6.2.2 Inventory Assets and Assess Capacity**

- **Regular reviews** should be carried out for airports and seaports in the region in the event of a lack of access during a disaster or increased demand for their services. Ensure there is ferry vessel/terminal compatibility by compiling and maintaining a register of existing and potential emergency ferry terminals, and their characteristics and requirements in the event of an emergency. This should also include an inventory of landings. Airports in Haiti, for example, had low capacity, were in a poor condition and did not

meet international standards. Post-disaster, these conditions heavily contributed to the crisis as poor transport infrastructure became a barrier to emergency aid and recovery.

- **Transit assets should be inventoried** (buses, vans, fuel supplies, communications equipment, and repair facilities) and key aspects of the assets listed (construction type, year built, footprint etc.).

#### **EVIDENCE 33: UK Local Resilience Forums and Community Resilience Units**

In the UK, local risk assessment is carried out by emergency responders—“blue light” services, local authorities, and front-line responders— under the Civil Contingencies Act. Local Resilience Forums (LRFs) were established under the Civil Contingencies Act 2004 to help prepare for emergencies. The Act stipulates that emergency responders must meet at least once every six months (Andrew, 2012). There are three categories of responders: Category 1 are the blue-light emergency services local authorities, the National Health Service, the environment agency, and other partners. Category 2 responders include the Highways Agency and the public utility companies. Wider partners include the military and the voluntary sector. LRFs collectively publish Community Risk Registers (CRRs) (Cabinet Office, 2011). A community resilience unit was also established in the UK Cabinet Office in 2007 to oversee and join work led by other departments such as the Environment Agency and the Department of Environment, Food and Rural Affairs (Defra) on community resilience. Communities are important in assessing risks and play a vital role in emergency preparedness and response. For example, agreements have been drawn up between local and the National Farmers Union to subcontract farmers and plant hire equipment to help clear access routes to isolated communities when there is snow (Andrew, 2012).

### **6.2.3 Collaboration Across Multiple Jurisdictions, Modes, Infrastructure Systems, and Actors**

- Transportation management centers can act as the nerve centers for monitoring traffic, emergency response, coordination, and travel advisories. They should also be clearinghouses for all information during a disaster and have an overview of all emergency preparedness issues, which can usefully feed back into planning (NCHRP, 2014).

- All transport operators should have **disaster contingency manuals**, which will immediately activate emergency procedures and establish a disaster response headquarter. These should also introduce redundancy into emergency operating systems so that if a disaster hits the main operating system there are procedures in place for a secondary unit to temporarily take over.
- **Coordinate across infrastructure systems** and share disaster contingency manuals between operators of different modes and infrastructure systems. Transportation routes often convey and are co-located with utilities, and these utilities are also essential for recovery and maintaining emergency power systems. The assumptions on which these manuals are based should be critically assessed and revised with other infrastructure operators if necessary.
- Operations and recovery planning has to integrate **private and non-profit sectors** into their planning; this has sometimes been done through non-governmental frameworks such as the All Hazards Consortium in the eastern United States (NHCRP, 2014).
- Communication protocols between the environment agency and transport operators as well as between weather forecasters and transport operators are important so that they can take adequate precautions to minimize disruption and ensure the safety of users.

#### **EVIDENCE 34: Transportation Management Center, New York**

TRANSCOM, the coalition of 16 major highway, transit, and public safety agencies in the New York, New Jersey, and Connecticut, had a series of regional conference calls the weekend before Sandy, including more than 100 officials from transportation facilities, police and emergency management agencies, and the governor's office. Members from Pennsylvania and Delaware joined the calls later as knowledge of the storm expanded. (NYS 2100 Commission, 2013: 71). Vermont Agency of Transportation (VTTrans) also used an Incident Command System decision-making framework to coordinate over a large number of jurisdictions and agencies. These were established in affected regions and coordinated by a unified command in the capital (FHWA, 2013).

#### **6.2.4 Contingency Plans and Transition Traffic Measures**

Highly visible contingency plans and transitional traffic

measures should be in place to identify alternative routes in the case of an emergency, particularly to major logistics facilities vulnerable to closure such as arterial roads, ports, and airports. A well-connected transportation system network that provides multiple links to each destination provides redundancy and flexibility in the system in the event of a disaster. This should include an assessment of where the most vulnerable and at-risk people are located and how they should be evacuated. Transitional traffic measures include:

- Exploiting redundant capacity in the system by adding extra ferry or bus services and maximizing the capacity and flexibility of other vehicles.
- Introducing temporary transit services such as bus bridges, bus lanes, and ferry services on routes with the highest priority.
- Assessing whether transport routes can be adapted in case of an emergency. San Francisco Planning and Urban Renewal Association (SPUR) recommended developing a plan for deploying diesel and hybrid buses on incapacitated electric bus routes (SPUR, 2012).
- Establish contraflow bus systems and emergency reserve bus fleets effective during an emergency (SPUR, 2012).
- Introduce mutual aid agreements between operators in advance, for example, between bus agencies and ferry operators to ensure there is spare capacity in the event of a disaster.
- Implement **high-occupancy vehicle requirements**.
- Locate emergency park-and-ride location in advance and draft websites and maps for circulation.
- Provide for bikes and pedestrians during an emergency to increase the transport system's resilience. Pedestrian and bicycle use rises significantly during a disaster whilst the government is mobilizing resources to begin the reconstruction process. Transport plans should provide for continuous bicycle and pedestrian routes to ensure the community's rapid recovery, and the overall resilience of the transportation system, which connects people to places. Bicycles can also be used by engineers and inspectors during the damage assessment of infrastructure.

- Introduce traffic measures to prevent further damage to infrastructure materials and prevent heavy goods vehicles from travelling on recently refurbished roads or on flooded roads as this deforms the surface.
- Provide indicators (in a similar way as “snowpole markers” are used to delineate the edge of the road) for road users to notice where the sides of the road are, and to indicate the flood depth, during inundation events.

#### **EVIDENCE 35: Alternative modes of transportation during Superstorm Sandy**

Superstorm Sandy highlighted the importance of alternative modes of transportation. Three new high-capacity point-to-point temporary bus routes that became known as “bus bridges” were put into effect and the lower level of Manhattan Bridge was turned into a bus only route. Ridership on emergency ferry services also increased by over 335 percent in an average weekday (NYC, 2013). In response to Sandy, NYCDOT also immediately restricted single-occupancy traffic as soon as subway outages were confirmed.

There was a sharp increase in bicycle use in New York following Sandy, from 3,500 users a day to 7,800 (though Citibike equipment was damaged during the storm). Through these measures, 74,000 people were able to cross the Manhattan Bridge by bus, foot, bicycle or private vehicle on November 2, 2012, more than three times the figure two days before when the bus bridge and HOV3+ (three occupants or more in a vehicle) rules were put into effect. In comparison, 87,000 people cross the bridge on a normal weekday (NYC 2013). Noting the hundreds of thousands of bikes left unused in San Francisco, SPUR (2010) recommended creating a Bicycle Emergency Response Team, made up of volunteers and paid professionals. The bicycle response plan would include: Shared bikes for short-term check-in and checkout; “below market rate bikes” for long-term use; “loaner” bikes at no cost but registered for return after the disaster; locations storage for bicycle pickup and check-in; picking up donated and low-end purchase and sell/lease/lend these, as well as fix those being donated;

establishing a media plan calling for bike donations/delivery; and communicating and inventorying a tracking system for people and bikes (SPUR, 2010: 25).

### **6.2.5 Coordinate and Standardize Emergency Equipment**

**Have on standby heavy equipment, mobile pump units, materials, and an emergency budget allocation.** Stockpile stocks of fuel, Bailey bridge components, and materials such as galvanized wire for making gabion boxes and hand tools.

Ensure that **other infrastructure equipment**—generators, battery back-up systems, and pumps—is installed at key locations and will be reliable and operational during an emergency.

**Locate plant equipment to clear rubble at strategic locations** along the main access routes allowing rapid access to blockages in the immediate aftermath of the event.

**Create statewide and regional pools** of hard to procure critical equipment that can facilitate rapid recovery and allow for continuous system upgrades. After Sandy, the MTA nearly exhausted its replacement supplies using more than 80 percent of supplies.

**Pre-printed signs** should be fabricated and stored. Standardize equipment across transportation agencies to improve redundancy and efficiency. Providing a uniform selection of critical equipment for signals and communications minimizes storage area, increases available replacement parts, and streamlines delivery.

**Agencies should coordinate to share inventory** thus ensuring redundancy across systems. These should not be located in hazard-prone locations (NYC, 2013).





Pouring concrete to plug the hole in the sea wall below Sea Lawn Terrace at Dawlish, UK, on February 24, 2014.

**Negotiate retainers with local contractors and labor groups** to ensure rapid mobilization in an emergency response. Companies can use their heavy equipment to secure immediate access to communities and undertake temporary repair to critical and damaged roads. It also saves transport agencies the expense of storing resources and taking care that they do not deteriorate.

#### **EVIDENCE 36: Community landslide early-warning system in Sri Lanka**

A community-based landslide early-warning system was implemented in Sri Lanka. It involved the community in capacity building through participation in hazard mapping, identification of safe areas, and participation in mock drills. These community aspects were done in conjunction with rainfall monitoring systems using a dynamic computer model to allow early predictions of landslide areas. The community also identified improvements to the emergency procedure by identifying problems with evacuation routes (ADRC, 2008). The relatively recent developments of the Internet and mobile phones all offer new communications mechanisms to better support more holistic approaches to DRM and communication in transport (National Research Council, 2006) (UNISDR, 2009).

### **6.2.6 Transportation Staff Access**

- Procedures should also be in place to mobilize and move staff from other locations that have not been impacted by the disaster.
- Critical personnel, where they live, full contact information, who is and is not likely to respond in an emergency, should be identified in advance.
- Coordinate with other critical infrastructure departments that have upstream/downstream interdependencies with transport infrastructure to ensure that there are emergency plans for their staff (particularly those operating pumps/levees, for example).
- Contingency plans for staff availability in times of extreme weather should be formulated and temporary personnel identified for times of extreme weather. Consideration should also be given to the need for staff lodging when weather is too bad for staff to get home.

### **6.2.7 Communication Systems**

Compatible and reliable communication systems between service providers and between service providers and road users must be available during an emergency.



- It is particularly critical that the means of communication between the many service providers are compatible and able to resist power cuts. Scalable backup communication systems can be created that work across various technologies (bandwidths, analogue or digital radios).
- Communicate resilience targets on the level of usability and the time it takes to restore ICT systems to manage user expectations. For example, targets could be set for a minimal level of service (for emergency responders)—functional (for the economy to begin moving again) and operational (near capacity).
- Service providers must also be able to communicate “vulnerable points” to road users to prevent traffic jams and accidents, as well as prevent further damage to the roads. Intelligent Traffic Systems can provide information for commuters and freight on alternative routes to be used—variable signs on roads, dedicated radio channels, mobile phone messages providing accurate and real-time information, Facebook, and Twitter.

#### **EVIDENCE 37: Communication during emergency response**

After the 2007 earthquake in Peru, national telecom operators and the Transport and Communications Ministry created a special emergency phone network to connect the presidential office, the police, fire departments, and health institutions (UNISDR, 2008).

Missouri’s Department of Transport reaches commercial vehicle operators through trucking organizations (FHWA, 2012).

Social media was particularly used to communicate with the public about the recovery effort in New York following Sandy. The Daily Pothole Tumblr, which documents NYCDOT street maintenance crews, was temporarily transformed into the “Sandy Recovery” page to document clean-up efforts. The number of Daily Pothole subscribers increased by 50 percent after the storm, to 15,000, as did NYCDOT’s Twitter and Facebook following (NYC, 2013).

### **6.2.8 Regular Monitoring and Review of Emergency Processes**

The monitoring and review of processes through a multi-stakeholder team will enable any problems and inefficiencies to be identified, and event, impact, and response scenarios to be modelled. This can be done through modelling simulations or simple exercises.

All the aspects covered above—coordination, information collection and exchange, communication processes, redundancy in the system, potential for flexibility; chains of command; the availability and prioritization of resources; and transportation options for critical emergency operators, commuters, and communities—should be regularly reviewed. Exercises should be planned on a regular basis and the relevant tools and evaluation guidelines provided to conduct these exercises. This also ensures that there is organizational learning and experience does not just rest with individuals (see Evidence 38).

#### **EVIDENCE 38: Monitoring and reviewing emergency processes**

Exercises can be as simple as questions such as “who would you call in an emergency” and “do you have their number,” “what would you do if power lines were down?” Exercises should be a learning activity as well as testing activity (NCHRP, 2014). In the UK, the Pitt Review was commissioned following the Gloucester floods in 2007 (Andrew, 2012).

This must be accompanied by the creation of **knowledge networks** to ensure previous lessons are utilized in the design of new policies, programs, and projects.

**Critical Infrastructure Modelling:** During Hurricane Katrina the water that overtopped unstable flood walls damaged transport infrastructure, delayed responding emergency services, and caused power outages that prevented flood pumps and hospitals from operating efficiently. In response, Idaho National Laboratory, supported by the U.S. Department of Energy, developed a software tool that visually portrays the dynamics of cascading effects and the way this affects the operation of emergency teams. They used simple maps or aerial photos and focused on the interdependencies of infrastructure in order to prioritize emergency response. The model can be updated and incorporated in a real-time view of the environment by building in webcams or direct sensor feeds. This allows emergency planners to run multiple infrastructure failure scenarios, and allows government agencies, utility companies, and first responders to identify the critical infrastructure links and prioritize where resources should be spent to increase the resilience of the region (Source: Idaho National Laboratory).

## 6.3 Expertise

Emergency staff capacity building involves training personnel to project manage emergency works. Regular emergency training exercises should be conducted to identify any weak spots and ensure that they are resolved. Highway maintenance workers should also be trained to obtain first-responder, operations-level training given that they are often the first employees to arrive on the scene of a disaster (Cambridge Systematics, Inc., 2004).

## 6.4 Financial Arrangements and Incentives

### 6.4.1 Flexible Emergency Budgets

Emergency budgets need a great level of flexibility as the need for a rapid response demands faster budget approval. Increased coordination is also required to deal with the complications arising from multiple actors using different budget mechanisms to channel funds. Funding can be diverted from existing programs and tendering processes shortened to provide more rapid support to emergency works required.

#### **EVIDENCE 39: Emergency budgets in Japan**

In Japan, for example, local governments report their infrastructure damage to the national government within ten days of a disaster and immediately request a national subsidy. Local governments can begin implementing their projects even before applying for the subsidy.

### 6.4.2 Catastrophe Bonds

Catastrophe bonds provide an immediate payout after the disaster has occurred and can be linked to emergency response plans, as well as to the level of adaptation built into the infrastructure by returning the savings from reduced damage or service interruption to investors (PricewaterhouseCoopers). A catastrophe bond (cat bond) allows risk to be transferred from an insurer or reinsurer into the capital markets thus increasing the amount of insurance that can be written. Furthermore, they are attractive to investors as a means of diversifying their investment portfolios as natural catastrophes are not correlated to existing economic conditions. Catastrophe bonds are index-based insurance mechanisms, where the indemnity is based on a specific weather parameter measure over a pre-specified period of time. Payout occurs when the index exceeds a pre-specified value. Index-based insurance is used when there is a strong quantifiable relationship

between weather risk and losses. More than USD 40 billion in cat bonds have been issued in the past decade, including in transport (see Evidence 40). Turkey issued a USD 400 million cat bond in April 2013 for earthquake protection (Keohane, G. L., 2014).

The main disadvantage, however, is basis risk—this is the potential mismatch between contract payouts and the actual loss experienced. Few of the 200 odd cat bonds that have been sold have generated a payout following a disaster (Keohane, G. L., 2014). For example, four storms in Haiti created considerable damage in 2008, but because most of this was due to flooding and not wind (the triggering parameter of the index-based coverage) a payout was not triggered by CCRIF. Further challenges to developing cat bonds in developing countries include the paucity and inadequacy of data required to develop and price products and the limited technical and financial expertise of domestic insurers to underwrite catastrophe risk.

#### **EVIDENCE 40: MetroCat Re and Superstorm Sandy**

Superstorm Sandy wreaked significant damage on New York's train, bus, and subway network, costing the Metropolitan Transit Authority (MTA) USD 4.75 billion to repair. As a result of significant price increases in the traditional reinsurance market, the MTA worked with its insurer, the First Mutual Transportation Assurance Company (FMTAC), to create MetroCat Re, the first catastrophe bond specifically designed to protect public transport infrastructure. It is a USD 200 million three-year cat bond where the payout trigger is linked to storm surge levels. If there are no storm surges above the specified thresholds before August 2016 the investors get their principal investment and returns of 4.5 percent annually above Treasury rates. Given these rates, the MetroCat Re was heavily over-subscribed (Keohane, G. L., 2014).

## 6.5 Technical Planning and Design, and Operations and Maintenance

### 6.5.1 Early-warning Systems

**Early-warning systems can be an important operational part of disaster-risk management within transport systems.** They take a variety of forms, from both the technologically advanced to relatively simpler community-based systems. For example, in Japan, the Central Japan Railway Company introduced automatic train controls on the Tokaido Shinkansen system in

2006, and also has an “Earthquake Rapid Alarm System.” This is part of a wider risk-management system comprising two general control centers (see Evidence 41).

#### **EVIDENCE 41: Japan’s urgent earthquake detection and alarm system**

Japan’s Urgent Earthquake Detection and Alarm System is made up of seismometers installed at 97 locations. Twelve-15 seconds before the 8.9 magnitude earthquake hit, a seismometer belonging to the country’s eastern rail operator sent an automatic stop signal to Japan’s high-speed bullet train’s electrical power transmission system, triggering the emergency brake on 22 trains.

Control of the system is from general control centers. In the event of a large-scale natural disaster, one center can assume the duties of the other should one become inoperable. Following detection of an earthquake, the system will issue an alarm to trains in two seconds. Automatic train controls (ARC) on the high-speed train system are linked to this and can stop a train to prevent accidents (Source: Central Japan Railway Company, 2013).

### **6.5.2 Emergency Repair Works**

**It is important for emergency repair works to get the right balance between taking immediate action and choosing the correct solutions with the longer-term recovery process and future resilience in mind.** In the case of Dawlish, the use of a temporary breakwater from shipping containers was an excellent example of preventing further damage, but also one in which the emergency response did not hamper or compromise the more permanent solution (see Case Study 22).

### **6.5.3 Disaster Waste Recovery (DWR)**

In the immediate period following a disaster, waste can be used for filling of holes/softspots and “lower-grade” road construction. Concrete is often the most widely available waste material, but other materials that can also be effectively used are brick, stone, and gravel. A

blended mix of virgin material/recycled material can be used as a solution in order to meet certain engineering specifications, or where DWR is limited. DWR can be applied to many construction projects, including roads, bridges, embankments, flood protection, kerbs, bedding for footways/paving, gabions, ballast for railway sleepers, airport runways, ports, and harbors.

There are technical challenges to get the right quality material for DWR. Consideration should be given to working with local crushing plants (usually associated with quarries), where the plant (crusher, screens) can be adapted to produce materials to the right specification. A challenge is to obtain “good quality” rubble that is free from non-construction material (household material, hazardous material, waste etc.). The logistics of the supply chain is important in relation to the waste DWR point. There are many factors to consider, including the trucking/transport available, clearance needs, storage, material available, production volume etc.

In order to institutionalize DWR, it is necessary to put in place regulatory frameworks, controls, and standards before a disaster to ensure quality and acceptance of materials, techniques, and specifications. Testing and certification of products and materials should also be incorporated into the process. Local/in-country training is also needed to establish the techniques and specifications of crushed material etc. before a disaster.

It can also be a challenge to gain widespread acceptance of DWR and overcome people’s perceptions of DWR material, both socially and culturally, as rubble could have been someone’s home once. Demonstrations and example specifications may help overcome negative perceptions of DWR and build capacity in this area. Furthermore, DWR can be linked to livelihood/income-generation schemes, as in Haiti where it has generated more than 100,000 hours of work for local men and women.

# 7

## 7.1 Introduction

Reconstruction of transport infrastructure involves the repair of critical infrastructure to a basic state of functionality sufficient to allow **recovery**, followed by the **reconstruction** of infrastructure, which builds in the lessons learned from previous performance, such that community resilience is enhanced against future disasters.

In order to quickly restore economic and social activities after a disaster there must be policies, institutions and processes, and financial arrangements and incentives *prior* to the disaster so that an investigation of infrastructure performance can be rapidly instigated after a disaster, and effective and contextually appropriate reconstruction measures deployed (Fengler, 2008). Below some key principles that would guide the thinking on how to first design projects that can help create an enabling environment, which will reduce recovery time and ensure that there is not a severe breakdown in income generation, as well as some aspects to take into account following a disaster, namely:

- **Infrastructure assessment:** An assessment of the infrastructure immediately post-disaster to consider how the system performed, where it failed and why;
- **Infrastructure performance analysis:** An analysis of the predicted performance of the system as designed during the construction phase in comparison with how the system performed in reality;

**Mitigation strategies:** Development of methods for addressing the failure mechanisms and targeting with project interventions. These should be categorized under the resilience principles that enable them to be targeted during the reconstruction process. This process will take time, which is often difficult to find in the aftermath of a disaster particularly when the focus

is given to promoting activities to enable communities to recover. There are a number of complex challenges in a post-disaster environment, which, if not prepared for adequately, can impair the quality of reconstruction and the resilience of the rebuilt transport infrastructure. A range of the key challenges are highlighted below.

- **Conflict between “like for like” versus “resilience.”** In most instances, reconstructed infrastructure is rebuilt to current design standards, which will increase the resilience of older assets that have not recently been retrofitted, but essentially continue to expose infrastructure to the same pre-disaster vulnerabilities (see evidence
- **Damage assessment and funding:** “Like for like” funding typically is only available for repair to the pre-disaster conditions and as such there is a challenge in identifying damage that is a direct consequence of the disaster. Further challenges to deciding what can and cannot be funded under “like for like” reconstruction is the difficulty in assessing what the actual network capacity loss is, the desired level of service to be restored, and “what constitutes added resilience.”

### EVIDENCE 42: “Like for like” versus “building back better”

Anecdotal evidence from many developing, and developed, countries suggests that assets are often rebuilt to the same pre-disaster standard and the cycle of exposure and vulnerability is continually repeated. New Zealand’s Stronger Christchurch Rebuild Team (SCIRT) recommended building back “like for like,” though identifying the source of the damage can be problematic. MacAskill (2014) discusses this issue in the post-earthquake rebuild in Christchurch, New Zealand. The stormwater network’s capacity was affected by land settlement



and reduced water capacity, but not by direct structural damage on the engineering assets, which is generally what qualifies for “like for like.” In one particular case in Christchurch engineers took into account the increased risk of flooding by going over and above “like for like” and adding a stormwater basin.

- There is a challenge in committing stakeholders to being actively involved and motivated in the process of reconstruction, beyond the emergency phase. The process is more costly, less attractive from a media perspective, and requires considerable commitment in time (Piper, 2011). There are **data collection and management issues after a disaster**, including: a lack of coordination where multiple teams may be collecting the same data and overlooking other perishable and critical data; lack of data repositories; difficulties in addressing issues of data access and maintenance; perishable data and different timeframes for data collection (Giovinazzi and Wilson, 2012).
- **The need for speed complicates the application of sound fiduciary principles.** The regular budget system is too rigid for the flexible response needed, whilst off-budget mechanisms face increased fiduciary risks and complicate coordination (Fengler, 2008).
- **Cost and time overruns.** According to an investigation by Sun and Xu (2011) of 72 projects in six cities of Sichuan Province, China, after the 2008 Sichuan earthquake, 32 percent of them suffered from time overrun and 82 percent had cost overruns (cited in Zhang, 2012).
- **Lack of transparency and account-ability.** In Aceh, Indonesia, 129 companies were blacklisted by BRR for various procedural violations. Economically or politically powerful groups often dominate the planning and decision-making process.
- **Absence of relevant and clear policies and legal systems** to guide, coordinate, and delegate responsibilities for efficient and resilient reconstruction.
- **A lack of communication and coordination** among stakeholders, including affected communities, asset owners, lifeline agencies, government and public agencies, non-governmental agencies, construction/reinstatement organizations and insurance companies.
- **Inadequate capacity and training** amongst personnel to deal with post-disaster reconstruction works and to coordinate and manage the long-term recovery and reconstruction, including the administration and leveraging of multiple funded projects.
- **A fragile construction market**, suffering from a scarcity of resources, inflation, and the unavailability of construction professionals and laborers. Insufficient involvement from the private sector also poses challenges to the coordination and management of reconstruction.
- **Resilience sacrificed for rapidity or cost saving.** Disaster remediation works tend to focus on restoring the basic functioning as quickly as possible to pre-disaster status without considering resilience. Budget constraints can mean resilience is seen as an additional cost. Fifty-four percent of respondents of the New Zealand Infrastructure and Buildings Construction Survey 2013 felt that addressing climate change impact in investment planning was of low importance, leading to missed opportunities in post-disaster reconstruction.
- **Conflicting donor and country regulations** in projects co-funded by donor countries. In Indonesia, the law states that in areas of conflict in co-funded projects donor regulations will prevail; implementation plans proposed by Indonesian contractors on USAID projects in Aceh were often delayed due to non-compliance with US regulations (USAID, 2007).
- **Boundary disputes and land acquisitions** are a common constraint. Acquiring land is a lengthy process and after a disaster records may be lost and government personnel may also be victims with little capacity and resource. In Aceh, issues with

land acquisition led to the expiry of funds for purchasing land for reconstruction (MDF-JRF, 2012).

- **Coordination between all agencies involved in**

## 7.2 Policies, Institutions, and Processes

Below are examples of the policies, institutions, and processes that will facilitate recovery and reconstruction following a disaster:

- Cross-agency reconstruction agencies are required to coordinate data sharing, speed assistance, maximize the efficient use of funds, and coordinate and harmonize the reconstruction process. The role tends to be coordination and monitoring, rather than implementation, either by (a) integrating a new coordinating agency into an existing ministerial system; or (b) creating a separate agency with specific authorities and responsibilities (WB, 2008: 8). If the nature of the disaster is large, the location remote, and local institutions weak then the need for a special agency is greater.
- Systems should be established for cross-agency information sharing and data storing. Some options include:
  - ∅ **Data menus:** In a disaster, local government personnel do not always know what information to ask for and where to find it. Each agency, including the transport agency, could develop a data menu containing a list of all datasets that are requested during a disaster. This should include the fields in the dataset, the units of measurement, how to use the data, and limitations. This document would be distributed to all disaster agencies at the local level.
  - ∅ **A data steward:** Each agency, including transport, and each state/local government could identify a “data steward” to act as a point of contact for data requests after and in advance of disasters (HUD, 2013).
  - ∅ **Interagency data portal** to allow agencies to access and store one another’s data. Agency attorneys and privacy officials could discuss what steps would be necessary to prepare the legal

**the reconstruction process.** A key challenge when reconstructing transport infrastructure is aligning reconstruction with other agencies, including other systems (utilities, electricity etc.), land-use zoning, and urban development.

framework for a multi-agency data portal (HUD, 2013).

**Geospatial information to allow teams to visually assess the condition of all asset, if they are being assessed and their prioritization** in the work program. It helps manage interdependencies between systems and service providers and reduces the number of times roads are dug up and construction teams can better coordinate, reducing costs considerably (HUD, 2013).

### EVIDENCE 43: Data collection and synthesis post-disaster

A unique feature of the Christchurch rebuild was the one-stop interactive digital map SCIRT used with its partners to collate all information. Agreements have been put in place with the energy companies to hold their asset data and represent it on this digital map.

In New York, an Office of Data Analytics was created to collect and synthesize data on the city’s essential services and engage with private and utility sectors following Hurricane Sandy (NCHRP, 2014).

- Infrastructure guidelines can be helpful during the reconstruction process to guide repair and replacement decisions. However, there also needs to be a mechanism in place to challenge and consider alternatives to the prescribed design standards.



Sinkholes and Liquefaction North New Brighton in Christchurch

**EVIDENCE 44: Christchurch SCIRT—  
Infrastructure Recovery Technical Standards**

Prescriptive Infrastructure Recovery Technical Standards and Guidelines were superseded as they were seen to be inappropriate for assets with residual operational life. The approach focused on returning a minimum service level across the city through repair, which allowed funding to be released for new infrastructure. The approach allowed balanced decisions about the most efficient use of the limited reconstruction funds, considering the resilience of the entire network, and undertaking cost-benefit analyses of initial capital costs, with the remaining asset life and the possibility of further earthquake damage (MacAskill, 2014).

- Pre-disaster contracting frameworks involve establishing long-term framework agreements between the client and contractors, consultants and suppliers, which enables rapid mobilization, effective risk sharing and collaborative working. Ultimately, this saves time, cost, and resources and lays the foundation for more resilient infrastructure.

**EVIDENCE 45: Pre-disaster contracting in Japan and Queensland**

In Japan, emergency agreements are drawn up between national and local governments and private sector partners. Potential partners are pre-qualified according to their financial, technical, managerial capacities, reputation, and past performance, and this framework agreement is regularly updated every few years. (Zhang, 2012). It is also in the interest of construction companies to participate in the relief and recovery effort as part of their business continuity plans (UNISDR).

Queensland also uses a system of pre-disaster contracting, and has also looked into procuring materials from industry suppliers in other countries as its capacities after the Queensland flood were overwhelmed and there was a shortage of basic construction inputs.

- Alliance contracting is an arrangement where parties enter into an agreement to work cooperatively and share risk and rewards measured against pre-determined performance indicators. The contractor's profit is earned through performance, reducing claims. It also promotes collaboration within a commercial framework between experts from different companies acting in the project's interest. This form of contracting has been adopted in the Stronger Christchurch Infrastructure Rebuild Team and one of the principle reasons that was put forward for using this form of contracting was to increase the "resilience" of the reconstructed infrastructure (see Case Study 23).

Flexible approaches to procurement: A central concern after a large disaster is understanding the capacity of the construction industry and the availability of materials, as well as ensuring that in releasing work out into the market this will not have the effect of overstressing construction companies or artificially driving up prices. New procurement approaches have been adopted to manage the scale of work after a disaster.

**EVIDENCE 46: Flexible procurement**

In Queensland, the Department of Transport and Main Roads developed a Performance Incentivized Cost Reimbursable Works Contract model that allowed the state to issue work to the market without

first defining the scope of the work. The department would work with the constructor to refine the scope of work and use a pain share/gain share arrangement. This has allowed the state to get projects out to the market faster, minimized disputes, and ensured the focus is on getting work done rather than administrating contracts (Low, P., 2013).

During reconstruction a clear monitoring and evaluation plan is critical. Progress must be monitored on a monthly basis and reconstruction programs need to react in real time to fast-changing situations on the ground. An overarching Results Framework can harmonize and integrate strategic priorities by measuring intermediate outcomes. Appropriate **performance indicators** should also be selected that can usefully measure actual results against expected results. **Performance evaluation task forces** can also be established after a disaster to assess why infrastructure failed and to ensure lessons are learnt during the reconstruction process.

#### EVIDENCE 47: Monitoring and Evaluation

In Aceh, Indonesia, the three common performance indicators (kilometers of road built, number of bridges and culverts built, number of bridges and culverts repaired) were too high level and could not capture the progress of construction activities. Specifically, clearing and grubbing, land fill, embankment, grading, layering, compacting, bridge piling, bridge fabrication, and asphalt paving (USAID, 2007).

A former director of research and development for the Army Engineers Research Corps chaired the Interagency Performance Evaluation Task Force, which conducted a two-year evaluation of how and why levees and flood walls failed during Hurricane Katrina in 2005. It also commissioned a study on the Hurricane Protection Decision Chronology. This was designed to document the chronology of the planning, economic, policy, legislative, institutional, and financial decisions that influence the hurricane protections systems of Greater New Orleans. The task force used those lessons to assist the Corps in developing new rules for building levees in the New Orleans area and nationwide (see Case Study 2).

## 7.3 Financial Arrangements and Incentives

### 7.3.1 Funding Sources

The challenge of reconstruction is the mobilization of additional resources over and above the normal development funding. Post-disaster recovery relies on effective fast-track funding that makes use of available

sources of financing, both internally and externally. It needs to consider both public and private financing, though for transport infrastructure, responsibility for repair and reconstruction is most likely to sit within the public domain. Practical ideas for various funding sources are found below:

- **Budget-sharing mechanisms between local and central governments:** Budget-sharing mechanisms between local and central governments allow local authorities to apply for additional funding for reconstruction works. The procedures should be negotiated in advance and cover the following: procedures for applying for a subsidy to the central government; the cost-sharing ratio of rehabilitation works; criteria for the types and severity of disasters, which require these mechanisms; establishment of a body of experts and organizations to the central government level and team formulation and procedures for damage assessment.
- **Special additional budget allocation:** Where regional budgets are insufficient, there may be options for requesting additional funding from national or international bodies.

#### Evidence 48: Bhutan—Monsoon damage restoration fund

The Department of Roads in Bhutan has a dedicated fund for the repair of roads and bridges after the annual monsoon. This funding is used primarily for the clearance, reconstruction, and reconnection of roads with little attention given to improving their resilience. This is despite the knowledge that there is often damage at the same locations each year.

- **Public-private partnerships:** Policy incentives can be used to promote private sector investment to share reconstruction costs. Public-private partnerships are often used to procure funds for infrastructure improvement, as it is seen as relatively low risk and suitable for long-term fund operation by pension and insurance institutions.
- **Regular budget:** Allowance for diversion of funding for existing projects to urgent repair work in the case of disasters.
- **Existing programs with international partners:** There may be options for negotiating for additional funds or diverting existing funds from international partners into post-disaster activities.
- **Loans:** If allowed by law, it may be possible to obtain



emergency loans, though this may impact on the future fiscal position of the country/province.

- **New taxes:** This is unlikely to be an attractive option, though theoretically possible. Levies, taxes or surcharges can be used to raise additional funds for reconstruction.
- **Policy incentives for boosting domestic trade and commerce:** Adopting changes to policy for commerce can promote investment and help to inject liquidity into affected areas.

**Disaster insurance:** Initiatives such as the Pacific Catastrophe Risk Insurance pilot are insurance programs aimed at helping to reduce the financial vulnerability of small island nations in the Pacific to natural disasters.

- **Recovery of private sector:** Promoting private sector recovery can promote collaboration in repair and operation of transport infrastructure, devolving responsibility and releasing resources. Infrastructure repair may rely on the private sector resources and providing support to these private enterprises can facilitate recovery.
- **Direct assistance:** Housing assistance with materials; livelihood restoration with free seeds, tools etc.; temporary income sources (i.e. cash-for-work); and alternative employment opportunities with retraining or referrals for rapid repairs or clearance of transport route.
- **Indirect assistance:** Temporary tax breaks; credit schemes to businesses with soft terms; and injecting equity to support recovery.

### 7.3.2 Financial Incentives

Emergency funding arrangements can also incentivize resilience to be mainstreamed within reconstruction projects and encourage pre-disaster planning, which will aid effective recovery and reconstruction (see Evidence 49 and 50). Practical ideas are found below.

- **Performance-based funding for disaster repair and reconstruction:** Resilient assessment criteria can be applied in the selection and prioritization of transport infrastructure investments, as has been done in New York following Hurricane Sandy.

- **Betterment funds:** Betterment funds can be established to restore or replace hazards to a more disaster-resilient standard than before. Betterment costs are the difference between restoring or replacing an asset to its pre-disaster standard and the cost of restoring or replacing it to a more disaster-resilient standard.

#### EVIDENCE 49: Incentivizing pre-disaster planning through funding conditions

The Natural Disaster Relief and Recovery Arrangement in Queensland provides funding to state and territories and has pre-agreed relief and recovery measures and a clearly defined threshold and cost-sharing formula. It also incentivizes mitigation measures by requiring states to implement disaster mitigation strategies as a precondition to receiving assistance for restoring or replacing public asset. If it has not implemented these, the assistance is reduced by 10 percent (World Bank 2011).

#### EVIDENCE 50: New York works task force—resilient assessment criteria

The governor and legislative leaders launched the New York Works Task Force in May 2012 to coordinate a statewide infrastructure plan to effectively generate and allocate the state's capital resources. The task force brings together professionals in finance, labor, planning, and transportation. This allows a more holistic analysis of needs and interdependencies. The NYS 2100 Commission worked with the New York Works task force to develop and then apply the following four resilient criteria in the selection and prioritization of infrastructure investments:

1) **State of good repair:** Whether the proposed repair, renovation or upgrade extends its life in a cost-effective way;

2) **Systems focus:** Whether investment benefits the economic or ecologic system in which it is located;

3) **Financial and environmental sustainability:** Whether the investment lowers ongoing or avoids future costs, including negative externalities such as damage to the environment;

4) **Maximize return on investment:** Whether the investment has a positive cost/benefit ratio over its entire lifecycle (Source: NYS 2100 Commission, 2013).



Loma Prieta earthquake damage on Bay Bridge, California, in 1989.

## 7.4 Expertise

There is a temporary increase in the reviewing and permitting activities required at all levels and plans should be made to ensure all agencies have the capacity to effectively manage and expedite these processes. This capacity building could include training sessions and workshops, one-on-one technical assistance, and peer-learning opportunities.

Further options include the creation of specific online portals offering tools, best practices, links to funding opportunities, a calendar all training and TA offerings in the region, blogs and discussion boards, updates on regional activities, and forums to request assistance from technical experts. New York is establishing such a portal (HUD, 2013: 138).

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## 8.1 Resilience Assessment Matrix

Selected section of the energy resilience assessment matrix from Roege, P.E., et al., (2014) Metrics for energy resilience, Energy Policy

	Plan and Prepare for	Refs	Absorb	Refs	Recover from	Refs	Adapt to	Refs
<b>Physical</b>	Reduced reliance on energy/increased efficiency	A,B, E,F, H	Design margin to accommodate range of conditions	B,C, I,J,K	System flexibility for reconfiguration and/or temporary system installation	C,D, F,H, K	Flexible network architecture to facilitate modernization and new energy sources	C,D, F,K
	Energy source diversity/local sources	A,E, F,H, K	Limited performance degradation under changing conditions	B,C, F,I,K	Capability to monitor and control portions of system	B,I, K	Sensors, data collection and visualization capabilities to support system performance trending	D,E, I,K
	Energy storage capabilities/presaged equipment	B,H, K	Operational system protection (e.g., pressure relief, circuit breakers)	I,J,K	Fuel flexibility	C,D, E,F	Ability to use new/alternative energy sources	C,F, H
	Redundancy of critical capabilities	D,E, I,K	Installed/ready redundant components (e.g., generators, pumps)	D,I, K	Capability to re-route energy from available sources	C,D, F,I,K	Update system configuration/functionality based upon lessons learned	C,D, L,F, K
	Preventative maintenance on energy systems	I,K	Ability to isolate damaged/degraded systems/components (automatic/manual)	E,I,K	Investigate and repair malfunctioning controls or sensors	I	Phase out obsolete or damaged assets and introduce new assets	A,C, D,I, K
	Sensors, controls and communication links to support awareness and response	H,I, K	Capability for independent local/sub-network operation	D,K	Energy network flexibility to re-establish service by priority.	F,I,K	Integrate new interface standards and operating system upgrades	D,I, K
	Protective measures from external attack (physical/cyber)	A,D, I,K	Alternative methods/equipment (e.g., paper copy, flashlights, radios)	B,H, K	Backup communication, lighting, power systems for repair/recovery operations	I,K	Update response equipment/supplies based upon lessons learned	D,I
<b>Information</b>	Capabilities and services prioritized based on criticality or performance requirements	B	Environmental condition forecast and event warnings broadcast	E,H, I	Information available to authorities and crews regarding customer/community needs/status	D,I	Initiating event, incident point of entry, associated vulnerabilities and impacts identified	A,D, H,I, K
	Internal and external system dependencies identified	B,G, H	System status, trends, margins available to operators, managers and customers	D,E, H,J, K	Recovery progress tracked, synthesized and available to decision-makers and stakeholders	D,I	Event data and operating environment forecasts utilized to anticipate future conditions/events	D,H, I,K
	Design, control, operational and maintenance data archived and protected	B,I	Critical system data monitored, anomalies alarmed	D,E, I,K	Design, repair parts, substitution information available to recovery teams	K	Updated information about energy resources, alternatives and emergent technologies available to managers and stakeholders	D,F, H,I

Figure 1: Energy Resilience Assessment Matrix (reproduced with permission from

**Table B.2 Technical resilience**

All-hazard assessment

Based on the principles of robustness, redundancy and safe-to-fail

Only score those elements that are relevant or of interest

Before beginning assessment, unfilter all cells and delete previous scores (to ensure no hidden cells are scored)

Select filter for asset/region, ie whether the assessment is for an asset or wider region (do not filter blanks)

At least one rating is required for each category

User to complete columns highlighted in blue only

Score

4.0 = Very high (3.51 – 4)	3.0 = High (2.51 – 3.50)	2.0 = Moderate (1.51 – 2.50)	1.0 = (0 – 1.50)
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ROBUSTNESS											Weighted robustness score		2,3	
Category	Measure	Filter: asset or regional (network) assessment	Item #	Item measured	Measurement	Measurement scale	Individual score	Category average	Weighting (%)	Weighted score	Note/ justification			
Structural	Maintenance	Region		Effectiveness of maintenance for critical assets	Processes exist to maintain critical infrastructure and ensure integrity and operability – as per documented standards, policies & asset management plans (eg roads maintained, flood banks maintained, stormwater systems are not blocked. Should prioritise critical assets as identified.	4 – Audited annual inspection process for critical assets and corrective maintenance completed when required. 3 – Non-audited annual inspection process for critical assets and corrective maintenance completed when required. 2 – Ad hoc inspections or corrective maintenance completed, but with delays/backlog. 1 – No inspections or corrective maintenance not completed.	3.0	2.8	33.33%	94.4				
	Renewal	Region		Establish asset renewal plans and upgrade plans to improve resilience	Evidence that planning for asset renewal and upgrades to improve resilience into system networks exist and are implemented.	4 – Renewal and upgrade plans exist for critical assets, are linked to resilience, and are reviewed, updated and implemented. 3 – Renewal and upgrade plans exist for critical assets and are linked to resilience, however no evidence that they are followed. 2 – Plan is not linked to resilience and an ad hoc approach is undertaken. 1 – No plan exists and no proactive renewal or upgrades of assets.	4.0							
	Design	Region			Suitability/robust-ness of critical asset designs across region	Percentage of assets that are at or below current codes	4 – 80% are at or above current codes 3 – 50-80% are at or above current codes 2 – 20-50% are at or above current codes 1 – Nearly all are below current codes				3.0			
					Condition of critical assets	Assessment of general condition of critical assets across region	4 – 80% are considered good condition 3 – 50-80% are considered good condition 2 – 20-50% are considered good condition 1 – Nearly all poor condition				3.0			
					Location of critical assets in areas known to be vulnerable to a known hazard (eg land slip, coastal erosion, liquefiable land, etc)	Percentage of assets that are in zones/areas known to have exposure to hazards	4 – <20% have some exposure to known hazards 3 – 20-50% are highly exposed, or >50% are moderately exposed 2 – 50-80% are highly exposed 1 – 80% are highly exposed to a hazard				2.0			
					Spare capacity of critical assets within region (in the event of partial failure, or surge in demand)	Percentage of critical assets with additional capacity over and above normal demand capacity	4 – 80%+ of critical assets have >50% spare capacity available 3 – 50-80% of critical assets have >50% available 2 – 20-50% of critical assets have >50% spare capacity 1 – 0-20% have spare capacity.				2.0			
Procedural	Standards/codes	Region		Existence of design codes to address resilience issues and risks. Update codes/standards to include resilience design principles into modern methods and materials (part of ongoing updates)	Existence of applicable updated design codes for all physical assets – which incorporate resilient design approaches	4 – Codes exist, have been implemented, are up-to-date and are applicable to all asset types 3 – Codes have been developed and updated, however, not implemented 2 – Codes are in existence but not updated 1 – No codes	2.0	2.0	33.3%	66.7				

**Section 8.2: New Zealand Transport Agency’s resilience assessment matrix.** Figure 2: Hughes, J.F., and K Healy (2014) Measuring the resilience of transport infrastructure. NZ Transport Agency Research Report, 546: 62



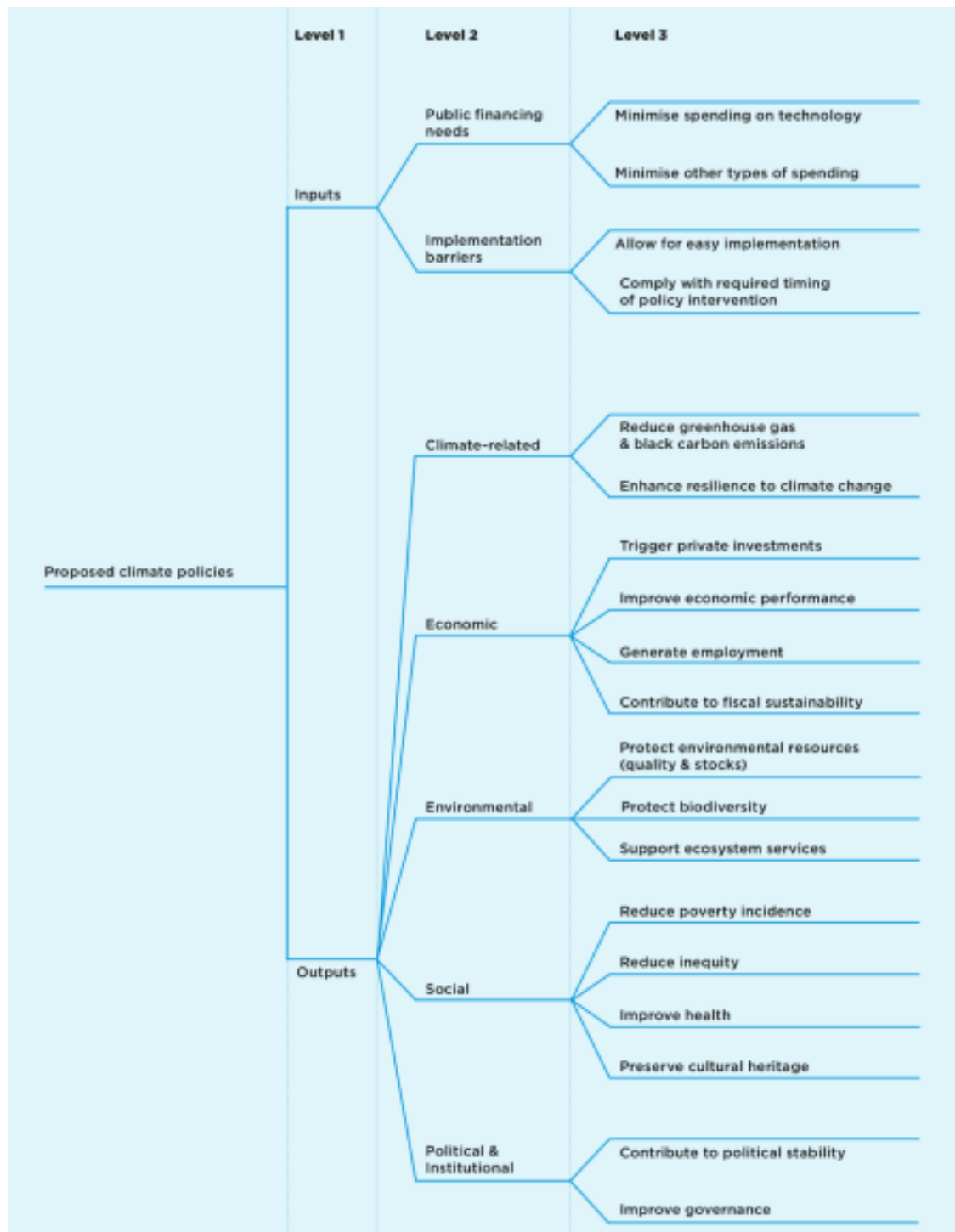
### 8.3 Infrastructure Interdependency Analysis

This tool has been developed by the Systems Centre, University of Bristol and the Bartlett at UCL, and was commissioned by used by HMT to map out the interdependencies between different infrastructure systems. The framework should be read clockwise. For example, starting from the energy sector box, what is the impact of the energy sector on ICT (box to the right) and what is the impact of the ICT sector on the energy sector (box to the left of ICT and under energy)? For the impact of energy on transport read two boxes to the right of energy and above transport, and for the impact of transport on energy read two boxes left from transport and two under energy. The overall framework is represented below as a snapshot of the ICT and Transport Sector interdependencies.

	P: Energy sector provides necessary electricity for operating and cooling ICT sector equipment (e.g. Server Farms)	P: ICT sector provides necessary fuel (petroleum) and lubricants to Transport sector (a) Energy sector provides necessary electricity for electrical and electric vehicles in the Transport sector	P: Energy sector is a source of general Waste transferred (as Waste sector) (a) Energy sector is a source of Nuclear Waste	P: Energy sector activities (e.g. Shale Gas) can transfer pollutants which contaminate ground water (a) Energy sector provides necessary electricity to Water sector for pumping etc. (a) Energy sector requires Water for cooling plant
<b>Energy</b>		C: Co-location, Energy sector activities and Transport sector assets share physical space		
	O: (1) Energy and ICT sectors can collaborate to create energy efficient equipment (a) Energy and ICT sectors collaborate on sharing data (provided by ownership issues)			O: Energy sector requires payment from Water sector for electricity provided to power pumps
P: ICT sector provides necessary resources to Energy sector			P: ICT components in space can become or produce space Waste	P: ICT sector requires protection from flooding provided by Water sector
D: ICT sector provides resources for Smart Grid, Smart Metering, Demand Management, Control and Billing in Energy sector	<b>ICT</b>	D: (1) ICT sector can potentially provide digital capability to reduce need for physical Transport (a) ICT sector provides resources and capability for Transport sector activities (a) Cognitive charging (b) 'Waste Water' (a) Multidimensional journey management (a) Global positioning (a) Control (a) Tracking (a) Block control (a) Road use charging	D: ICT sector provides the capability for Waste and recycling 'logistics' Road use charging	D: (1) ICT provides the capability for Smart Metering and management of Water Water sector (a) ICT provides the capability for digital control of Water Water sector
O: (1) ICT sector provides necessary control and communications systems to Energy sector during outages (a) ICT sector and Energy sector can collaborate to reduce ICT energy footprint (a) ICT and Energy sectors collaborate on sharing data		O: (1) Some ICT plants and facilities are geographically linked to the Transport network (a) Co-location of some ICT physical assets (e.g. servers, cables and some Transport assets (e.g. roads))		
O: (1) ICT sector provides data management capability to Transport sector (a) ICT sector and Transport sector collaborate on sharing data (a) ICT sector provides capability for general operational usage within Transport sector		O: ICT sector and Water sector collaborate on sharing data		O: ICT sector and Water sector collaborate in sharing data
P: (1) Transport sector provides the capability to move Shale Gas (a) Transport sector provides the capability to move fuel to power stations (a) Transport sector (a) transfer excess heat from vehicle tunnels into Energy sector	P: Transport sector provides capability for (a) delivery for ICT sector	<b>Transport</b>	P: (1) Transport sector provides the necessary capability to move Waste (a) Transport sector creates Hazardous Waste which requires disposal	P: (1) Transport sector can potentially provide (a) an abstraction to Water or (b) facilities to transfer (a) permeability of materials used to construct Transport sector assets can affect Road risk
D: Transport and Energy sectors share intelligence information	D: Transport sector relies on ICT sector for Road use charging capability			
C: Co-location of Transport and Energy assets				C: Co-location of Transport and Water assets to provide utility corridor
O: (1) Transport sector requires network for Electric Vehicle (EV) charging (a) Sector policies result for digital or other goals (a) variety of use and reduction in domestic energy use			O: Transport and Water sectors can collaborate to change behaviour on emissions (b) usage, work, log etc.)	O: Transport and Water sectors can collaborate on flood management planning rules
P: (1) Waste and byproducts can potentially provide a resource for the Energy sector including processes such as Amenable Algalgae (a) Waste can potentially provide a source of raw Earth metals needed by the Energy sector		P: Waste sector requires Transport for (1) Movement of hazardous waste (a) Movement of general waste (a) Movement of specific materials that cannot be disposed locally (e.g. nuclear byproducts)	<b>Waste</b>	P: (1) Waste sector can potentially produce contaminated water which is transferred to the Water sector (a) Waste in landfill can potentially cause more Water runoff
				C: Co-location of Waste facilities and Water resources can potentially result in ground water contamination
O: Waste disposal plans may need to be in place before new power stations are approved (especially Nuclear)		O: Segregation of Waste at source and separation of Waste at a dedicated facilities have different transport needs (and affect Efficiency versus Quality)		
P: (1) Water provides a potential means to generate electricity (a) Water provides a necessary means of cooling Energy plant (a) Water provides a potential means of Energy storage (a) Water sector may require Energy for Bulk Water Transfer		P: Water sector provides flood protection for Transport sector assets		
	D: Water sector relies on ICT Sector for Smart Meters and Demand Management			<b>Water</b>
		O: (1) Co-location of Transport assets and Water resources can increase the risk of Flooding (a) Water utilities can disrupt Transport network by digging up roads (a) Water sector utilities can disrupt road system due to such standard maintenance		
O: Water sector provides payment to Energy sector for Pumping	O: Water sector collaborates with ICT sector for real time data capabilities to maintain efficiency, energy use and resilience			

**Figure 3: Infrastructure Interdependencies** reprinted with permission from: Engineering the Future (2013) *Infrastructure Interdependencies Timelines*. London: Royal Academy of Engineering. p.10. Available: [www.raeng.org.uk/ETF-Infrastructure-Interdependencies](http://www.raeng.org.uk/ETF-Infrastructure-Interdependencies)

## 8.4 Generic Decision Tree: MCA4 climate policy evaluation framework



**Figure 4: MCA4 Climate Policy Evaluation Framework**, Source: Hallegatte, S., (2011) MCA4climate: A practical framework for planning pro-development climate policies, Adaptation Theme Report: Increasing Infrastructure Resilience

## 8.5.1 FLOODING

Table 1: Flooding Failure scenarios

FLOODING FAILURE SCENARIOS	CONTEXT
<b>Inadequate drainage</b>	<p>(i) The hydraulic size or gradient of culverts is inadequate resulting in blockage/silting of culverts from sediment or debris, wash out of embankments, or loss of culverts; and (ii) the longitudinal drainage channels or outfalls are overwhelmed. These failures can result in the inundation of the <b>road/railway</b>.</p> <p>This is of particular concern for <b>runways and taxiways</b>, and <b>large paved areas in ports</b>.</p>
<b>Inundation and raised groundwater levels</b>	<p>(i) Weakens/erodes sub-grade, capping layers, sub-base layers, and wearing on gravel, paved or earth <b>roads</b>; (ii) causes road distress from increase in groundwater levels and soil moisture (pore pressure effects caused by wheel loads and mobilisation of plasticity in fine fracture); (iii) causes foundation weakness/failures beneath <b>ballast/track</b> in flooded deep/long cuttings on flat gradients; (iv) causes degradation of bearing capacity of supporting foundation (loss of material strength and stiffness);</p> <p><b>Bridges/tunnels:</b> Deterioration of structural integrity due to an (i) increase in soil moisture levels (acceleration in the degradation of materials, increased ground movement) (ii) changes in the groundwater affecting the chemical structures of foundations and fatigue of structures; (iii) ingress of groundwater through tunnel linings</p> <p><b>Inundation of tunnels:</b> excessive groundwater flows, overland flows or raised/water river levels damage tunnel linings</p>
<b>Inadequate capacity</b>	Water flows exceed capacity resulting in overtopping of <b>bridges</b>
<b>Erosion/ Scour</b>	Impact on <b>bridges</b> and <b>inland waterways</b> . Undermining of substructure elements (abutment and pier) and/or erosion of approach embankments; Excessive flows cause erosion of the river banks and induce erosion/scour of training walls, weirs, tow paths, ramps, gauges etc.
<b>Floating or sunken debris</b>	<p>Debris builds up against intermediate supports or under bridge deck soffits, and sunken debris increases scour depths due to increased turbulence</p> <p>Debris can build up against inland waterway structures and weirs, increasing loads on these structures. Water levels upstream and sunken debris can particularly increase scour depths due to turbulence.</p>
<b>Movement backfill to abutment</b>	Clay in the fill materials used in <b>bridge</b> design can expand or contract under prolonged precipitation or inundation.
<b>High water level</b>	This can create navigation problems on <b>inland waterways</b> where there are bridges or other structures with limited headroom, or where there is limited channel freeboard on supporting embankments.
<b>Aggradation</b>	Accumulation of sediment carried by high water flows can block <b>inland waterways</b> restricting operations and raise water levels upstream.

## Linear Infrastructure (Roads and Railways) Measures: Flooding

Most of the resilience measures are focused on increasing robustness, with the exception of swales, Irish crossings and embankment overtopping (safe failure) and planning alternative routes (redundancy). In general, robustness of infrastructure tends to be increased through hard or soft engineering measures to strengthen the protection works (embankments, drainage systems, culverts) as opposed to stronger pavement construction itself. Such measures often increase overall resilience of the built environment with high embankments providing access, acting as flood defences for urban areas and refuge for displaced communities in cases of severe flooding.

**Table 2: Technical Assessment Sheet - Linear Infrastructure, Flooding**

	PIPS	EXPERTISE	OPERATIONS AND MAINTENANCE	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Use soft engineering techniques ( <b>green infrastructure</b> ) and adaptive management	●	●	●	●	●
Incorporate <b>Sustainable Urban Drainage Systems (SUDS)</b> principles in the design.	●	●	●	●	●
<b>Hydrological and drainage design</b> should be carried out considering not only historical data but also predicted increase in annual precipitation and higher water and river levels.	●	●		●	●
Plan for/provide <b>alternative routes</b> in the event of a road/railway closure. (Example of <b>redundancy</b> ).	●	●			●
<b>PREPARATION AND DESIGN</b>					
<b>Allow undersized culverts to be overtopped</b> by designing for such failures ( <b>Irish Crossings</b> ). (Example of <b>safe failure</b> ).	●	●	●	●	●
Construct roadway over embankments to accept the passage of flood waters at defined locations ( <b>swales</b> ). (Example of <b>safe failure</b> ).	●	●	●	●	●
<b>Elevate vulnerable road segments.</b>	●			●	●
<b>Allow embankments to overtop</b> in extreme flood events. (Example of <b>safe failure</b> ).	●	●	●	●	●
<b>IMPLEMENTATION</b>					
Use <b>appropriate embankment materials</b> - rock fill at bridge approach; granular materials	●	●	●	●	●
<b>Increase longitudinal drains' capacities</b> - ensure road drainage is routinely shaped by grader, protect verges and channel side slopes with appropriate vegetation cover, ensure effective longitudinal drainage capacity in cuttings to remove flood water.	●	●	●	●	●
<b>Provide cutting slope drainage</b> - adequate and effective drainage cut off drains installed to top of cutting slopes, berms etc.	●	●	●	●	●
<b>Harden river defences</b> – retaining walls, gabion baskets, earth dikes, random rubble, etc.	●	●	●	●	●
<b>Increase protection of susceptible materials against salinity</b> (e.g. corrosion resistant reinforcement to culverts and bridges; higher concrete strength and increased cover).	●			●	●
<b>Use robust pavement structures</b> - erosion resistant surfacing, concrete better than asphalt better than surface treatment better than gravel; chemically stabilised base materials (cement stabilised)	●	●	●	●	●
<b>Protect culverts</b> against erosion (rock armour, stone pitching, gabions)	●		●	●	●
Construct embankments in accordance with the international designs standards <b>using materials appropriate for low earth dams.</b>	●	●		●	●

### **Bridges Measures: Flooding**

Similar to the flooding of roads and railways, most of the resilience measures are focused on increasing robustness, with the exception of designing for submerged bridge deck and letting bridge embankments being washed away in a major flood event (safe failure) and design as a floating bridge or so bridge deck can be elevated at some future date (flexibility). The robustness measures are split between those that increase the design strength or overall scale of the bridge structure (e.g. increased openings larger spans, increased clearances to bridge soffit) and attendance to associated measures such as upstream reforestation and SUDS to dampen the design hydrograph for the watercourse, reducing peak flood flows and preventing the build up of debris causing scour. In other cases robustness can be achieved at the planning stage through introducing vehicle load restrictions. This case shows the range of different measures that can be deployed to increase the overall resilience of transport infrastructure.

**Table 3: Bridges, Flooding**



	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>					
<b>PLANNING</b>					
Put in place <b>vehicle load restriction</b> to minimise structural damage due to subsidence and the loss of bearing capacity;	●	●	●	●	●
<b>Manage road surface water run-off</b> (side drains and slope drains) to prevent damage to fill or cut slopes near abutments	●	●	●	●	●
<b>Limit flood flow velocities</b> by increasing the size/number of bridge openings.	●	●	●	●	●
Let bridge approach embankments be washed away to relieve flood restrictions in the case of exceptional flooding. This would be an example of <b>safe failure</b>	●	●	●	●	●
<b>Limit flood flow velocities</b> at bridge opening through upstream works (e.g. Snags, bends, upstream reforestation).	●	●	●	●	●
Prevent build-up of debris against intermediate supports or under deck soffit through <b>upstream river and development management</b> (see also Operations and Maintenance, and Governance)	●	●	●	●	●
<b>PREPARATION AND DESIGN</b>					
<b>Provide maintainable back of wall drainage</b> as well as weep-holes to abutments and wing walls to allow the rapid dispersion of water pressure from behind walls.	●	●	●	●	●
Provide <b>scour protection</b> around bridge abutment, wing wall, piers as well as at associated minor culverts and headwall/toe wall.	●	●	●	●	●
Design using <b>larger spans</b> and / or <b>limiting the number of intermediate supports</b>	●	●	●	●	●
<b>Deepen foundation depths</b> , harden river bed; gabion mattresses, rock fill, etc.	●	●	●	●	●
Design <b>bridge and bridge decks</b> to be submerged during extreme flood events; this would be an example of <b>safe failure</b> .	●	●	●	●	●
Increase <b>design flows for critical infrastructure</b> and other high investment structures above standard practice (1 in 100/1 in 500).	●	●	●	●	●
<b>Provide cut-off sheet piling</b> to protect foundations	●	●	●	●	●
<b>Using piled foundations</b>	●	●	●	●	●
Increase <b>vertical clearances</b> of bridges soffit	●	●	●	●	●
Design bridge so it can accommodate the permanent <b>raising of the bridge's deck at a future date</b> (e.g. steel beams vs RC slab deck, abutment/pier's foundations strong enough). This would be an example of <b>flexibility</b> .	●	●	●	●	●
Design as a <b>floating bridge</b> . This would be an example of <b>flexibility</b> .	●	●	●	●	●
<b>IMPLEMENTATION</b>					
Install <b>debris guards/racks upstream</b> either at new structures or retrofitted to existing structures.	●	●	●	●	●
Select <b>appropriate granular material</b> together with tight construction supervision to ensure adequate compaction behind abutments and retaining walls.	●	●	●	●	●
Protect bridge approach embankment slopes and river banks by <b>providing paving, stone soiling or gabion baskets/mattresses</b> .	●	●	●	●	●
Improve material quality with <b>mechanical or chemical material stabilisation</b>	●	●	●	●	●

## Inland Waterways Measures: Flooding

In general the measures listed increase robustness through improved protection (river banks, trash gates to avoid built up of debris/sediment).

**Table 4: Inland Waterways, Flooding**

MEASURES	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
	IMPLICATIONS				
<b>PLANNING</b>					
Provide an adequate number of <b>strengthened mooring facilities</b> for waterway traffic, and to moor up during high flows.	●	●	●	●	●
<b>PREPARATION AND DESIGN</b>					
Provide <b>adequate drainage capacity</b> at the toe of an embankment to convey any flood water.	●	●	●	●	●
<b>Protect banks from flood flows</b> (and vessel wash): hardening, vegetation and speed limits.	●	●	●	●	●
Provide <b>extra freeboard</b> to sections raised on an embankment.	●	●	●	●	●
<b>IMPLEMENTATION</b>					
Provide <b>trash gates</b> and other defensive barriers to trap debris and protect structures.	●	●	●	●	●
<b>Remove obsolete structures</b> if causing problems (e.g. trapping sediment).	●			●	●
<b>Raise side embankments</b> to reduce flood risk and/or increase channel freeboard; extend side weirs, retrofit gates and so on to accommodate changes in water level and flow; replace ineffective bank protection with environmentally friendly climate-proofed protection.	●	●	●	●	●

## 8.5.2 LANDSLIDES: ALL INFRASTRUCTURE

**Table 5: Failure scenarios**

LANDSLIDE FAILURE SCENARIOS	CONTEXT
<b>Surface runoff/ ingress into slopes</b>	The main trigger will often be the intensity of short, extreme rainfall. This can affect the stability of slopes due to surface runoff over or ingress into the slopes. <b>Roads, railway and tunnel</b> infrastructures are most susceptible to landslides; especially as a result of human interference e.g. deep mountainous cut (rock falls and landslides), diversion of overland water flows onto slopes (land and mud slides).
<b>Water-level changes</b>	Rapid changes at the groundwater level along a slope can also trigger slope movement affecting <b>roads, railways, bridges and tunnels</b> .
<b>Erosion</b>	Water flows down the slopes or flows across the toe cause erosion of toe support. Rates of erosion are increased by unstable soils and steep slopes. This impacts <b>roads, railways and bridges</b>

	Rivers carrying debris from landslides can cause scour, erosion of river bank and approach embankment; scour cause damages to the <b>bridge</b> substructures' foundations.
<b>Wildfire</b>	Loss of the roots of plants and trees that hold the soil together from wildfire triggers movement of soil affecting <b>roads, railways, bridges, and tunnels</b>
<b>Snowmelt</b>	In many cold mountain areas, snowmelt can be a key mechanism by which landslide initiation can occur, affecting <b>roads, railways, bridges and tunnels</b>
<b>Ground Movement</b>	Removal of slope support by general ground shaking or by liquefaction of the soils during earthquakes, <b>affects all infrastructure</b>

### All Infrastructure Measures: Landslide

All of the measures listed improve robustness of the infrastructure, through a combination of better drainage and/or increased robustness of embankments, soils and slopes. This approach can limit the risk of catastrophic failure by isolating vulnerable areas and enabling re-stabilisation of slopes and ensuring that failure does not replicate.

**Table 6: Technical Assessment Sheet - 2All Infrastructure, Landslides**

	PIPS	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Remove or prevent uncontrolled water flows at slopes through	●	●	●	●	●
Remove or prevent uncontrolled water flows at slopes through <b>better slope drainage systems to capture of water</b> . This could include cut-off drains or improved slope drainage (e.g. chutes, herringbone drains, pipes).	●	●	●	●	●
<b>Strengthen river training</b> and toe retaining structures to prevent landslides impacting water bodies.	●	●	●	●	●
<b>PREPARATION AND DESIGN</b>					
<b>Stabilise slopes using bio-engineering</b> (e.g. Grasses, shrubs or trees).	●	●	●	●	●
<b>Chemically stabilise soils</b> (e.g. using vinyl, asphalt, rubber, anionic and non-ionic polyacrylamide (PAM), or biopolymers).	●	●	●	●	●
<b>Stabilise an incipient landslide</b> by constructing (to provide a shear key and buttresses); flattening the slope (to decrease the driving force of an active slide) and stabilise by unloading the road grade (formation/foundation).	●	●	●	●	●
<b>IMPLEMENTATION</b>					
<b>Reinforce slopes using geo-textiles</b> (e.g. geofabrics, geocells, geo grids).	●	●	●	●	●
Provide <b>rockfall netting, catch trenches</b> and/or <b>concrete rock shelters</b> along vulnerable locations.	●	●	●	●	●
<b>Reshaping the surface of slopes</b> (e.g. through terraces or benches, flattening over steepened slopes, soil roughening, or land forming).	●	●	●	●	●
<b>Use mechanical stabilisation techniques</b> (e.g. rock, gabion baskets, concrete, steel pins, rock anchors, toe retaining walls).	●	●	●	●	●

### 8.5.3 WAVES AND HIGH TIDES (HURRICANES, CYCLONE, TYPHOON)

**Table 7: Failure Scenarios**

Extreme low pressure can induce high precipitation (flooding), higher tides and storm surges, more damaging waves and extreme winds.

CYCLONE/ HURRICANE FAILURE SCENARIOS	CONTEXT
<b>Inundation</b>	<p>(i) Raised sea levels, exacerbated by wave action results in the overtopping of sea defences. This weakens the bearing capacity of the <b>roads</b> and <b>railway</b> track beds. It also saturates embankments and weakens soft <b>coastal defence structures</b>.</p> <p>(ii) The overtopping of sea defences causes scour and erosion to protective <b>breakwater, wave walls and quay walls</b>.</p> <p>(iii) <b>Road embankments</b> and <b>rail beds</b> can be washed away</p> <p>(iv) Flooding of <b>tunnel</b> entrances</p>
<b>Scour/ Erosion</b>	<p>(i) Scour and erosion to <b>protective sea walls</b> and <b>returning walls</b> causes damage to structures including: <b>roads</b> and <b>railways</b>, <b>trackside</b> and <b>road side furniture</b>, <b>dockside super structures</b> such as warehouses, cranes and <b>overhead utilities</b>; <b>boundary structures</b> such as noise barriers, high brick walls and timber fences; and <b>abutments, piers, foundations, approach embankments</b> and <b>service culverts</b>.</p> <p>(ii) Scour can also occur at <b>river banks</b> through the transportation of sediment during high waters which can create further sediment build up.</p>
<b>High lateral wind speeds/ gusts</b>	<p>(i) Effects on <b>vehicles/vessels</b>. Vehicles are susceptible to overturning (especially high sided freight vehicles) and trains. Wind can impact <b>planes</b>, especially at subsidiary air strips either while planes are landing or taking off, or while parked on stands. The airplanes will maximize their possibility to land and take-off into the wind, but, this is not always possible due to the existing runway orientation or due to sudden wind variations, for example due to high hills etc. adjoin the airport. In practice, air-planes often operate under crosswind and sometimes tailwind conditions. For safety, cross-and tailwind values are restricted to certain limits above which flying operations are curtailed. High winds may also affect the navigation of vessels, for example the Danube closed to the Iron Gates. In such an instance, navigation of pushed convoys in ballast without bow thrusters may be suspended. Due to the large wind lateral area of the <b>vessels</b> above the waterline, the side forces acting on the vessel may become so high that safe manoeuvring may not be possible using only the propulsion devices of the pusher.</p> <p>(ii) Cable sag or tension failure of <b>overhead cables</b> and other <b>overhead utilities</b> (reduces the spacing/clearance between the cables, trees, building) such as due to being torn down by <b>train</b> pantographs,</p> <p>(iii) Damage to <b>tall structures</b> e.g. supporting pylons, signs and posts, cranes, overhead utilities, control towers, navigational equipment and communication systems, and support buildings in <b>ports</b> and <b>airports</b></p> <p>(iv) Loss of <b>street furniture</b>, including traffic signs, lighting columns, traffic signals, service ducts, and power cables.</p> <p>(v) Instability of <b>boundary structures</b> such as noise barriers, high brick walls (older structures) and timber fences (strength of the shallow foundation affected by wind load);</p>

	(vi) Harmonic vibration or uplift of <b>bridge</b> deck or superstructures. High bridges are more prone to extreme wind events and bridge signs, overhead cables and tall structures (lamp columns) face increased risk from the greater wind speed.
<b>Falling/ flying debris</b>	(i) Damage to infrastructure - <b>bridges, runways, terminals, navigational equipment, perimeter fencing, signs, banks and training walls</b> - from flying items, structural or natural; (ii) Damage to infrastructure from collapsing or falling elements, structural or natural; (iii) Debris blocks <b>drains, culverts, rivers</b> , etc. (iv) Trees, power lines and debris blocking <b>road and railways, ports entrances, river junctions, tow paths</b> and other rights of way. (v) Debris (such as driftwood) can damage infrastructure, including <b>vessels</b>

### All Infrastructure Measures: Waves and High Tides

These measures combine a more critical design of infrastructure to survive higher wind specification of hurricanes (and subsequent increased design strength and therefore robustness of transport infrastructure) and ancillary and protection measures such as clear lines of site, avoiding vulnerable high ancillary structures. In some cases safe failure is proposed for jetties in non-critical locations.

**Table 8: Technical Assessment Sheet - All Infrastructure, Waves and High Tides**

	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Impose <b>free tree zone</b> or clear rights of way/line-side of vulnerable trees.	●	●	●	●	●
Use <b>mobile cranes</b> in ports instead of fixed high cranes. (Example of <b>flexibility</b> ).	●	●	●	●	●
Where high and large sea defences are not feasible environmentally or	●	●	●	●	●
Ensure <b>redundancy of critical infrastructure and systems</b> (e.g. navigation)	●	●	●	●	●
Strategies for <b>cross wind effects</b> whereby runways are constructed parallel to the pre-dominant wind direction and outside of the effects of nearby high land.	●	●		●	●
<b>Harden strategic coastal defences</b> . For example utilising wave walls, rock armouring, dikes, seawalls, rocks apron, breakwater systems can be used to fend off rising sea level or storm surges.	●	●	●	●	●
<b>Safe failure of jetties in non-critical locations</b> .	●	●	●	●	●
<b>Avoid installing high ancillary structures</b> on susceptible bridges (e.g. overhead power lines across a bridge).	●	●		●	●
Place <b>overhead services underground</b> .	●	●	●	●	●
<b>PREPARATION AND DESIGN</b>					
Design <b>vulnerable critical features to accommodate (more) extreme wind effects</b> (e.g. radars, control towers, etc.).	●	●	●	●	●
Bollards – increase designed windage forces ships for new bollards; identify, test and <b>upgrade critical existing bollards</b> .	●	●		●	●
Design for <b>aerodynamic effects</b> on structural members in accordance with standard international practice.	●	●		●	●
<b>Strengthen the wind load specification</b> used in the designs.	●	●		●	●
<b>IMPLEMENTATION</b>					
<b>Strengthen supporting brackets</b> to overhead power cables and utilities.	●	●	●	●	●
<b>Strengthening and heightening of existing levees, seawall and dikes</b> behind sea defences.	●	●	●	●	●



## 8.5.4 EARTHQUAKES

**Table 9: Failure Scenarios**

EARTHQUAKE FAILURE SCENARIOS	CONTEXT
<b>Liquefaction</b>	<p>(i) Liquefied soil forces its way to the surface, breaking through <b>roads, railways</b> and <b>runways</b>, causing uplift, subsidence and voids. This uplift of the transport structure also damages underground infrastructure <b>drainage</b> and surface drainage systems, and services such as <b>utilities, tanks, pipes</b> and <b>manholes</b>.</p> <p>(ii) On slopes, the ground ‘slides’ on the liquefied layer. Cracks and fissures can occur at the extremities of the slide;</p> <p>(iii) Uplift damages <b>underground infrastructure services</b> such as utilities, tanks, pipes, and manholes;</p> <p>(iv) Contamination of the materials in the <b>road</b> from the liquefied soil.</p> <p>(v) Lateral spreading from liquefaction can apply pressure to <b>bridge</b> abutments, reducing bearing capacity or reducing the integrity of the structure. It also applies pressure to <b>quays</b> and <b>seawalls</b>, reducing their bearing capacity and the integrity of the structure. Many <b>ports’</b> facilities are constructed on fill materials placed over historic wetland. Such materials are generally fine and granular in nature and susceptible to liquefaction if provisions are not made to resist such force or relieve the pore pressure resulting from higher water table and seismic shaking.</p>
<b>Structural failure</b>	<p>(i) Surface and sub-surface water <b>drainage</b> system failure</p> <p>(ii) Failure of <b>utility</b> and <b>traffic control</b> systems;</p> <p>(iii) Major/severe cracks which have the following effects: damage to the <b>carriageway</b> surface; disorientation of <b>railway</b> track and track buckling; shear failure of <b>pier, abutment, deck</b> and <b>surface</b>; the <b>tunnel</b> lining leading to damage/collapse</p> <p>(iv) Damages to <b>structures</b>, like storage buildings, paved storage area, storage tanks/cranes/heavy equipment/shipping containers/heavy cargo due to ground movement/shaking, runways, taxiways, control towers, radar systems, fuel facilities and supply facilities</p>
<b>Land/ Mudslides</b>	Refer to the failure scenarios and approaches under section under LANDSLIDES
<b>Tsunami/Wave /High Tide</b>	Refer to the failure scenarios and approaches under section Road/Railways under TSUNAMI/EXTREME LOW PRESSURE (WAVE/HIGH TIDE)
<b>Flooding</b>	Refer to the failure scenarios and approaches under section Bridges/Tunnel under FLOODING

## Ports and Airports Measures: Earthquakes

These measures reflect the desire to maintain operation of airports after an extreme event. Therefore all of the measures listed increase robustness except measures about relocation or provide alternative airport provision elsewhere in the case of such an event occurring.

**Table 10: Technical Assessment Sheet - Ports and Airports, Earthquakes**

	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Ensure <b>other structures</b> such as storage buildings, storage tanks and cranes are <b>capable of accommodating potential seismic events safely</b> .	●	●		●	●
Consider building <b>lower capacity alternative airfields/airports in other locations</b> (as in Belize) as a less costly alternative to building resistant runways. This is an example of <b>redundancy</b> .	●	●		●	●
<b>Relocate runway</b> where runways/taxiways are built in vulnerable location on soils conducive to liquefaction.	●	●		●	●
<b>PREPARATION AND DESIGN</b>					
<b>Design foundations to withstand potential seismic events</b> even if structures are damaged.	●	●	●	●	●
Provide <b>seismic designs for equipment mounted in ceilings</b> .	●	●		●	●
<b>Design critical infrastructure to withstand greater seismic events</b> than other buildings or structures (e.g. fuel supplies, radar installations, provision of seismically sound supports to provide base isolation to avoid damage to equipment in Air Traffic Control Towers).	●	●		●	●
<b>IMPLEMENTATION</b>					
Provide <b>comprehensive soil improvements</b> , which could include installation of stone columns to support the runway pavement.	●	●		●	●

## 8.5.5 TSUNAMI

### Failure Scenarios

Tsunamis are ocean waves produced by undersea earthquakes or landslides. Tsunamis are often incorrectly referred to as tidal waves, but a tsunami is actually a series of waves that can travel at speeds averaging 450 to 600 mph (725 to 965 kph) across the open ocean. The reports from the 2011 Japan earthquake (Chock, 2013) noted that tsunami waves reached a height in excess of 10 metres. The waves rushed inland almost as far as 10 kilometres in some locations. Tsunami waves can therefore cause significant damage to transport infrastructure, even when it is remote from the coast. Defensive infrastructure is expensive and generally cannot be considered to be cost effective except for very high risk sites (e.g. nuclear power stations).

**Table 11: Failure Scenarios Tsunami**

TSUNAMI FAILURE SCENARIOS	CONTEXT
<b>Debris</b>	<p>(i) A tsunami creates exceptional amounts of debris as it destroys buildings and other structures, or picks up boats, vehicles, containers and the like and carries them forward. The debris exacerbates the damaging effects of the wave as it sweeps inland. As the wave's forward motion wanes a backwash wave is generated. The back wash wave and the debris carried, continue to damage infrastructure, particularly the landward side of sea defence structures which have not been designed to resist such effects.</p> <p>(ii) Debris will block <b>roads</b> and <b>railways</b> and whole <b>drainage</b> systems, in particular channels/soak-ways/pipe systems/manholes/culverts</p>
<b>Inundation</b>	(see Flooding failure scenarios) Loss of bearing capacity of <b>road</b> pavement and <b>rail</b> bed (increase level of moisture content) weakens the strength and stiffness of the soil properties
<b>Scouring and Erosion (including landward)</b>	<p>(i) Scour and erosion damages <b>road</b> pavements and <b>rail</b> bed embankments and associate structures</p> <p>(ii) Damages <b>abutment, piers, foundation, approach embankments, and service culverts</b> are subjected to scour and erosion</p> <p>(iii) Weakens the stability of <b>jetty, quay wall, seawalls</b> or <b>barriers</b></p> <p>(iv) Concrete lined <b>earth barriers</b> can suffer heavy scour and erosion</p> <p>(v) Large <b>segmental walls</b> are susceptible to overturning after scouring due to overtopping flow. Lack of continuity between elements allows quick development of failures.</p> <p>(vi) <b>Caisson-type breakwaters</b> founded on rubble mounds are susceptible to sliding and overturning</p>
<b>Wave force/speeds</b>	<p>(i) Wash way of <b>road embankment</b> and <b>rail bed, quay wall, seawalls, barriers</b> or <b>breakwaters</b></p> <p>(ii) Losses of <b>street furniture</b>, including traffic signs, lighting columns, traffic signals, service ducts, and power cables.</p>

	<p>(iii) damage/destruction to large <b>sluice gate structures</b>, and <b>back of quay infrastructure</b>, including offices, administration building storages, sheds access road, railways and other terminal facilities.</p> <p>(iv) Uplift of <b>bridge</b> deck or superstructures</p> <p>(v) Overturning or uprooting of <b>bridge</b> substructures</p>
<b>Debris</b>	<p>(i) Debris often accumulates on the side of <b>structures</b> and this can result in damming effects that may increase the lateral load on the structures;</p> <p>(ii) Damaged <b>seawall</b> can generate massive debris which can travel with inflow,</p> <p>(iii) Accumulated debris at <b>inland waterway</b> entrance channels and <b>sluice gates</b> can cause damage</p>

### Linear Infrastructure (roads and railways) Measures: Tsunami

Only limited measures for protecting linear transport infrastructure against tsunamis is provided. While some protection is anticipated in vulnerable areas it may be better to ensure that that some failure of infrastructure in extreme cases is accepted, and design carried out to limit rebuild costs, if possible.

**Table 12: Technical Assessment Sheet – Linear Infrastructure, Tsunami**

	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING/PREPARATION &amp; DESIGN/IMPLEMENTATION</b>					
Plan and design (where feasible) for main road and railways to be built above the tsunami maximum inundation levels and/or beyond reach of both inflow and backflow effects of the tsunami.					
Where roads and railways are built within reach of tsunami effects provide protection against erosion and scour on embankments, both for inflow and outflow.					

## Ports and Airports Measures: Tsunami

Coastal airports are particularly vulnerable to high wave action or tsunami and in particular airports on small islands. In the event of a tsunami, the major structures that may be affected are runways, taxiways, drainage system and underground utilities, as well as hanger and terminal buildings. As airports are critical infrastructure which need to be operational soon after a disaster the prime measure here is locating airports out of likely affected areas, or maximum inundation levels. The provision of emergency landing on a stretch of highway is an example which will create redundancy in the system, thereby increasing overall robustness.

**Table 13: Technical Assessment Sheet - Ports and Airports, Tsunami**

	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Design or <b>upgrade sections of highways on higher land for STOL (short take-off and landing) aircraft</b> to carry out emergency evaluations and post disaster relief.	●	●		●	●
<b>Consider relocation of coastal airports</b> to an alternative sites on higher land or where protected from the coast by higher land (this is an example of <b>redundancy</b> ).	●	●		●	●
Provide <b>alternative emergency airstrips</b> away from Tsunami danger zones thus ensuring <b>redundancy</b> .	●	●		●	●
<b>PREPARATION AND DESIGN</b>					
Design ports with a <b>better understanding of tsunami</b> refraction and diffraction.	●	●		●	●
Design seawalls with <b>adequate piled foundations</b> in tsunami zone areas.	●	●	●	●	●
Design to prevent the total loss of piers, wharf walls and their tiebacks and restrain selected breakwater panels to <b>provide post-tsunami access</b> .	●	●	●	●	●
<b>IMPLEMENTATION</b>					
<b>Review strength of existing barriers</b> and strengthen if required (e.g. through provision of concrete-lined earth barriers).	●	●	●	●	●
<b>Review the strength of existing coastal protection or breakwaters</b> (particularly the number and/or size of armour unit/rock protection) and increase if required.	●	●	●	●	●



## Bridges Measures: Tsunami

These measures mainly increase robustness of the structure itself. Some of the measures here may conflict with design principles that address other hazards.

**Table 14: Technical Assessment Sheet – Bridges, Tsunami**

	PIPS	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Build above tsunami maximum inundation levels and beyond the reach of both inflow and backflow effects of a potential tsunami, where possible.					
Provide alternative routes and temporary by-pass roadways to increase redundancy.					
Review strength of existing bridge decks for seismic tsunami loads (including vertical uplift restraints) and retrofit where existing bridge decks are insufficient.					
Comprehensively assess vulnerability of existing structures for failure/collapse in seismic and potential tsunami prone areas. An appropriate assessment approach (or equivalent) should be based on Seismic Design Categories (SDC), AASHTO (2009 - 4 seismic categories, A, B, C and D).					
<b>PREPARATION AND DESIGN</b>					
Ensure new bridges are designed to resist lateral/vertical loads from potential tsunami flow. Design for hydrodynamic lateral loads and for both hydrostatic and hydrodynamic uplift due to anticipated tsunami flows.					
Where practicable, ensure bridges are designed so that potential flexural overturning failures of entire piers/connected multiple bridge girder spans occur at connections so that foundations are protected (an example of safe failure). In practice, this will not apply in areas of seismic risk, as this will conflict with resilience against seismic events.					
Ensure structures are designed to accommodate both seismic dynamic loading and tsunami hydrodynamic loading, including hydrostatic and hydrodynamic uplift due to the anticipated tsunami flow.					
<b>IMPLEMENTATION</b>					
Ensure seismic shear keys are sufficient to restrain lateral movement of bridge decks (i.e. Sufficient lateral restraint provided).					
Restrain bridge decks against uplift from and removal away from their supporting piers and abutments. Ensure that the buoyancy of bridge decks (such as the effects of air trapped between girders) is considered in the design of tension anchorages.					
Provide erosion and scour protection for bridge substructures and approach embankments, both for inflow and outflow.					

## 8.5.6 EXTREME HEAT

### Failure Scenarios

Extreme heat can damage infrastructure. The effects are however magnified as a consequence of its combination with periods of extreme cold in the same location (e.g. east European summers and winters). Extreme heat does not significantly damage ports and inland waterway infrastructure. However, supporting infrastructure in particular access roads, concrete structures, signs, overhead cables, surface markings, etc. suffer the same effects as described in Road and Railways and Airports above. One potential impact to navigation, in particular on inland waterways, is a reduction in the water level (due to evaporation and an increase in the speed of seasonal hydraulic cycles). In addition, an increase in the average temperature could lead to increase growth of invasive aquatics vegetation leading to the clogging of water supply lines and drains as well as increased demand for cleaning, maintenance and dredging.

**Table 15: Failure Scenarios, Extreme Heat**

EXTREME HEAT FAILURE SCENARIOS	CONTEXT
<b>Expansion and Buckling</b>	(i) Leads to <b>rail</b> track movement and slack (thermal misalignment) causing derailment; (ii) sag of <b>over power cables</b> ; no balancing weights to take up the thermal expansion <i>(Note: Extreme and extended periods of heat reduces precipitation which in turns leads to increase risk of wildfires which can damage transport infrastructure)</i>
<b>Concrete pavement failures</b>	Inadequate expansion joint provision or maintenance thereof leads to the failure and lifting and deformation of one or more joints as the <b>road</b> pavement expands. The effects are magnified if the road must accommodate significant contraction during cooler periods. This also affects <b>ports</b> and <b>airports</b>
<b>Bitumen/Asphalt degradation</b>	Heat will affect and reduce the life of the <b>road</b> through softening and heavy traffic related rutting or bleeding. However, high temperature differences can also coincide with high levels of ultraviolet radiation (due to strong sunlight) to cause the bitumen/asphalt to oxidize, becoming stiffer and less resilient, leading to the formation of cracks. This also affects <b>ports</b> and <b>airports</b>
<b>Degradation of road foundation/ rail bed and supporting embankment</b>	A decrease in soil moisture leads to deformation of the <b>road</b> pavement structure which leads to potholes, cracks and rutting. This also affects <b>ports</b> and <b>airports</b>
<b>Deformation of Marking materials</b>	Premature deterioration of the material properties. This affects <b>roads, railways, bridges, tunnels, ports</b> and <b>airports</b>
<b>Materials degradation</b>	(i) Premature degradation of bearings and deformation of <b>structural</b> members: (ii) degradation of <b>runway/taxiway</b> foundation and supporting <b>embankment</b>
<b>Thermal Expansion and increased movement</b>	(i) Extra stress: Expansion of <b>bridge</b> joints and paved surface; (ii) Excessive movement of bearings, closing of movement joints gaps.
<b>High Air temperature</b>	The extreme heat or rise in temperature induces lower air density, a factor that reduces the thrust produced by <b>aircraft</b> and the wing's lift.

## Linear Infrastructure (Roads, Railways, Airports and Ports): Extreme Heat

In general the measures listed here increase the robustness of the infrastructure through changes in the materials used or design specification. The increased size of movement joints is an example of how infrastructure can be made stronger through increased flexibility within the design itself. Similarly the use of control systems shows how increased robustness of a system may rely on its operation and governance rather than the design and maintenance of the physical infrastructure itself.

**Table 16: Technical Assessment Sheet – Linear Infrastructure, Extreme Heat**

	PIPS	EXPERTISE	O&M	TECHNICAL			COST/FINANCE
MEASURES	IMPLICATIONS						
<b>PLANNING</b>							
Increase use of <b>heat tolerant street and highway landscaping</b> to reduce	🟡	🟡	🟢	🟡			🔴
To accommodate higher air temperatures extend or design a <b>longer runway</b> (the International Civil Aviation Organisation recommends an increase of the runway length of 1% for each 1° C).	🟡	🟡		🟡			🔴
Increase the use of <b>efficient ground cooling systems</b>	🟡	🟡	🟡	🟡			🔴
Use <b>information and control systems</b> to prevent unnecessary road/rail use in extreme heat situations (particularly heavy loads).	🔴	🟡	🔴	🟡			🔴
<b>PREPARATION AND DESIGN</b>							
Design using <b>more robust pavement marking materials</b> that can withstand seasonal changes. (e.g. thermoplastics road marking materials are suitable for high temperatures.)	🟡	🟡	🟢	🟡			🟡
Ensure <b>adequate movement joints and/or gaps</b> on structures to prevent deformation of members due to excessive expansion.	🟡	🟡		🟡			🟡
<b>Increase specification for bridge bearings and expansion joints</b> to account for extreme heat effects which take account of greater expansion/contraction movements. This will include specification of appropriate bearing elastomers to prevent premature degradation due to excessive heat.	🟡	🟡		🟡			🟡
<b>IMPLEMENTATION</b>							
<b>Avoid using concrete pavement expansion joints</b> by constructing Continuously Reinforced Concrete Pavements (CRCP).	🟡	🟡	🟢	🟡			🟢
Use <b>heat resistant asphalt/stable bitumen</b> to ensure better performance in higher temperatures.	🟡	🟡	🟢	🟡			🟡
Use different type of <b>passive refrigeration schemes</b> , including thermosiphones, rock galleries, and “cold culverts” (NRC 2008)	🟡	🟡	🟢	🟡			🟡
<b>Raise the Rail Neutral Temperatures</b> used in design, and associated lateral restraints, combined with operational constraints as necessary to reduce buckling.	🟡	🟡	🟡	🟡			🟡

## 8.5.7 EXTREME COLD AND SNOWSTORMS

### Failure Scenarios

The impacts discussed here relate to the direct impacts of very low temperatures and snow storms/blizzards. For the effects consequent upon the melting of accumulations of snow please refer to the sections above in regard to excess precipitation and FLOODING. The main impacts on transportation relate to the operation of the infrastructure rather than the infrastructure itself. Good maintenance practice, such as sealing and repairing roads before the winter months are necessary to mitigate the risks from extreme cold.

**Table 17: Failure Scenarios, Extreme Cold**

EXTREME COLD FAILURE SCENARIOS	CONTEXT
<b>High frequency-thaw cycle</b>	(i) Premature deterioration of <b>road</b> pavements (moisture in the foundation freezes and thaws causing a volume change within the materials). Increased freeze-thaw conditions in selected locations creates frost heave and potholes on road surfaces. This also impacts <b>ports</b> and <b>airports</b>
<b>Frost/Icing/Freezing</b>	Ice on <b>railway</b> tracks leads to poor adhesion, ineffective braking (skid, loss of traction, wheel spin); <b>rail</b> points/switches not able to move due to being frozen in one position, which may lead to derailment;-brittle fracture of rail track and steel structures (at least 20°C below design level).
<b>Snow/Blizzards</b>	(i) Drifts block <b>railway</b> lines and build-up on <b>signals</b> ; (ii) Dead loads in excess of the strength of the structure damage <b>station roofs, overhead power lines, signs and gantries</b> ; (iii) powdered snow ingested into <b>vehicles</b> and <b>trackside equipment</b> can cause loss of function of trackside equipment
<b>Ground movement</b>	Caused by freeze thaw cycles and also caused by Permafrost melting results in cracks or causes the <b>road</b> to slide (results in slope failure, sinkholes and potholes). It can also dislodge large boulders and rocks, causing mud/landslides (see LANDSLIDES). This impacts <b>roads, railways, ports</b> and <b>airports</b>
<b>Excessive contraction</b>	Opening of movement joint gaps in <b>bridges</b> due to excessive contraction; bearing failure
<b>Damage/failure of structural members</b>	Brittle failure of steel structural members; spalling of concrete arising from permeable and saturated concrete; concrete substructure damaged by ice flows; excessive build-up of ice on structural members; deformation of structural members. Impacts <b>bridges, airports, lock gates and weirs</b> .
<b>De-icing /Anti-icing Chemicals</b>	Contamination of surface water and drainage outfalls, such as through operational de-icing of <b>aircraft</b> due to cold weather

## Roads, Railways, Airports and Ports: Extreme Cold

All of the measures listed increase robustness of the infrastructure. The location of a runway to avoid permafrost is an example of how planning can increase robustness. The inclusion of retention ponds to reduce the scale of impact of de-icing chemical shows how the choices made to increase transport infrastructure resilience can have wider impacts.

**Table 18: Technical Assessment Sheet - Extreme Cold**

	PIPs	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Avoid locating runway and taxiways on permafrost due to rising temperatures.	🟡	🟢	🟢	🟢	🟢
Consider locations and factors that <b>avoid increasing the intensity of extreme cold</b> (e.g. frost and snow hollows) in project design.	🟡	🟡	🟢	🟡	🟢
<b>Review whether surface dressing is appropriate</b> (for road pavement resurfacing)- as in cold countries with greater freeze-thaw effects this has a lower performance as when a binder exposed to direct frost it can become brittle and allow water to penetrate into the pavement.	🟡	🟡	🟡	🟡	🔴
<b>PREPARATION AND DESIGN</b>					
<b>Increase pavement thickness</b> to prevent frost penetration into frost susceptible soils.	🟡	🟡	🟢	🟡	🔴
Design bridge substructures and river training infrastructure to <b>resist iceflow damage</b> and the lateral forces applied.	🟡	🟡	🟢	🔴	🔴
Design structural members and joints/bearings of bridges to withstand extreme cold, and <b>design for ice build-up loads</b> on these members and the structure as a whole.	🟡	🟡	🟢	🔴	🔴
In extreme cases, consider installation of systems to <b>heat road pavements</b> .	🟡	🟡	🔴	🟡	🔴
<b>IMPLEMENTATION</b>					
Provide permanent (and temporary) <b>snow (blizzard) barriers</b> .	🟢	🟢	🟢	🟡	🟢
Eliminate environmental impact of de-icing pollutants through provision of <b>retention ponds</b> to control and separate polluted run-off from paved areas with that from grassed areas thereby reducing the volume of water at risk of pollution.	🟡	🟢	🟢	🟢	🟢
Ensure good quality design and construction practices to <b>minimise spalling of concrete</b> (e.g. Use higher strength and self-compacting concrete).	🟡	🟡	🟢	🟡	🟢
Install systems to <b>heat frozen points and signal heads</b> on railways.	🟡	🟡	🟡	🟡	🔴
Use new <b>advanced road studs and marking types</b> that respond to low temperature to warn drivers of freezing temperatures on the surface of the road.	🟡	🟡	🟡	🟡	🔴



## 8.5.8 WILDFIRE

### Failure Scenarios

Wildfires, also termed bushfires or forest fires, are unplanned fires which can be extremely hazardous to infrastructure and life and can spread rapidly over large areas from the initial fire start point. Periods of extremely hot dry weather (combined with low humidity), provide ideal conditions for the outbreak of wildfires. Whilst typically associated with hot weather, wildfires are not exclusively summer events and wildfires can occur even in very cold winter conditions.

**Table 19: Failure Scenarios, Wildfire**

<b>WILDFIRE FAILURE SCENARIOS</b>	<b>CONTEXT</b>
<b>Combustible materials</b>	Assets which are combustible will be damaged in fire. Wooden, bridges and wooden railway sleepers are very vulnerable.
<b>Roadside verges and railway verges – vehicles</b>	Roadside verges can create favourable conditions for fires to start- either through ie discarded cigarettes, parking (hot parts of vehicle contacting combustible material), or providing access for deliberate and starting illegal fires.
<b>Power lines and trees</b>	Trees can damage power lines or electrical equipment, especially during storms when both can be affected by wind or storms. Damaged power lines can start wildfires.
<b>Poor management of transport assets</b>	During wildfires roads may need to be closed due to fire risk. Good network management and asset management is needed to facilitate access/egress for public and emergency response teams according to fire management scenarios.

## Roads, Railways, Airports and Ports: Wildfire

Fire prevention is often a much better strategy than mitigating against the effects of fire damage, but due to the nature of the risk, this is not always possible and fire risks should be assessed and managed in a systematic way so that these assessments can help inform mitigation works and technical decisions. They will also help in managing transport networks during a fire, particularly with regard to life-saving activities. In certain high fire risk areas, restricting development is one option, but practical measures to reduce combustible material, especially at roadside verges, are extremely important in reducing fire risk. Other technical measures, such as replacing concrete railway sleepers can reduce overall damage levels.

**Table 20: Technical Assessment Sheet – Wildfires**

	PIPS	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
<b>Plan control lines</b> (natural or constructed barriers) or treated fire edge used in fire suppression and prescribed burning to limit the spread of fire. Control lines are only likely to be effective if they are <b>supported by suppression activities</b> and hence need to be in areas of low fuel. Careful consideration needs to be given to the placement of control lines if they are to be effective, and because they can involve significant and ongoing vegetation management which can degrade environmental and heritage values.	●	●	●	●	●
<b>Prioritise and rate the risk of assets</b> (including people and property) according to hazard (likelihood of exposure and consequence of fire). <b>Make use of GIS mapping</b> to disseminate information where appropriate				●	●
Assess mitigation measures in accordance with fire risk to <b>determine vegetation management regime</b> and other mitigation actions.			●		●
<b>Safeguard critical routes</b> and access (public bunkers, community fire refuges etc).			●		●
<b>PREPARATION AND DESIGN</b>					
Consider <b>fire-resistant vegetation</b> species when carrying out roadside planting.			●	●	●
On roadside verges, keep a vertical <b>separation between fuel and vehicle</b> (10cm height one vehicle width (3m) adjacent to road shoulder or on trafficable verges through verge management/clearance works.	●	●	●		●
For rail, select <b>non-flammable materials</b> where appropriate (ie concrete instead of timber) where appropriate for 'sleepers' or rail ties. Initial costs may higher, but whole life cycle costs may be better				●	●
Transport infrastructure buildings to be <b>resistant to ember attack</b> .			●	●	●
<b>Incorporate control lines or fire breaks</b> in roads where appropriate (see Planning Note above) – remove trees and cut back vegetation. Use bare earth breaks. Trees even 20m upwind can reduce effectiveness of break. Use of control lines (firebreak).	●	●	●		●
<b>IMPLEMENTATION</b>					
Through regulation, enforcement and education, a <b>'fuel-free' road shoulder verge should be maintained during fire danger period</b> , where required (for example; limit or eliminate combustible material).	●	●	●		●
Carry out management (clearance and removal) of trees around power lines to <b>prevent damage and sparking ignition sources</b> .	●	●	●		●

### 8.5.9 FLASHFLOOD/MUDFLOW

A flash flood is a surge of water, usually along a river bed, dry gully or urban street often following a period of intense rainfall. Conducive conditions for flash floods are mountainous areas, hilly and steep slopes which act as a highly responsive watershed. The hazard can:

- develop over very short time periods
- can occur even if no rain has fallen at the point where the flooding occurs
- erode loose material, soils and topsoils and turn into mudflows

Other causes of landslides include landslide dam outbursts (where landslides block a river and create a natural dam which is breached suddenly, glacial lake outburst flows (GLOF), sudden bursting of river banks and failure of 'engineered' water retaining structures.

**Table 21: Failure Scenarios, Flashfloods/Mudflows**

FLASHFLOOD/ MUDFLOW FAILURE SCENARIOS	CONTEXT
<b>Inadequate drainage</b>	(i) the hydraulic size or gradient of culverts is inadequate resulting in blockage/silting of culverts from sediment or debris, wash out of embankments, or loss of culverts; and (ii) the longitudinal drainage channels or outfalls are overwhelmed or there is no slope drainage.
<b>Inadequate capacity</b>	Water flows exceed capacity of the allowable resulting in overtopping of bridges or damage to bridge deck.
<b>Erosion/ Scour</b>	Impact on bridges and inland waterways. Undermining of substructure elements (abutment and pier) through scour and/or erosion of approach embankments; Excessive flows cause erosion of the river banks and induce erosion/scour of training walls, weirs, tow paths, ramps, gauges etc.
<b>Floating or sunken debris</b>	Debris builds up against intermediate supports or under bridge deck soffits, and sunken debris increases scour depths due to increased turbulence. Debris can build up against inland waterway structures and weirs, increasing loads on these structures, especially damaging or destroying bridge decks. Water levels upstream and sunken debris can particularly increase scour depths due to turbulence.
<b>Aggradation</b>	Accumulation of sediment carried by high water flows can block inland waterways restricting operations and raise water levels upstream.
<b>Sudden release of stored water</b>	Landslide dam outbursts (where landslides block a river and create a natural dam which is breached suddenly. Reducing landslides is covered under separate studies but some points are reiterated in this case study), glacial lake outburst flows (GLOF), sudden bursting of river banks and failure of 'engineered' water retaining structures.
<b>Environmental/ Social</b>	Changes in land use, such as infrastructure development (roads, housing etc) can increase impermeable area and volumes of overland flows. Roads can act as conduits for overland flows.

## Roads, Railways, Airports and Ports: Flashflood/Mudflow

The damaging effects of flashfloods/mudflows can often be predicted through the modelling of overland flows. Solutions can include early warning systems which are linked to meteorological data. Infrastructure should be designed for the correct design peak discharges with allowances for debris build-up at structures. Scour is a well-known risk for hydraulic structures, and care must be taken in any design work in this area. Bio-engineered solutions are an important part of mitigation and should be considered alongside hard-engineering solutions where appropriate.

**Table 22: Technical Assessment Sheet, Flashflood/Mudflow**

	PIPS	EXPERTISE	O&M	TECHNICAL	COST/FINANCE
<b>MEASURES</b>	<b>IMPLICATIONS</b>				
<b>PLANNING</b>					
Understand vulnerabilities to flash floods by making an <b>assessment of catchments and water flows</b> . Speak to communities and those with <b>local knowledge</b> . Review evidence for historic events – scars, steep valleys etc	●			●	●
<b>Consider multi-hazard assessments</b> . For example a landslide across a river can cause water to back up dangerously. This event could take place far beyond the point of consideration. Glacial Lake outburst (GLOFs) and similar events represent similar hazards.				●	●
Consider <b>land use planning</b> and the vulnerabilities this creates – land clearing and loss of vegetation can promote flash floods and mudslides. Settlements and the most vulnerable are often located on the most hazard prone areas.	●			●	●
Understand the <b>geology/hydrology/meteorology</b> of the region. For example reducing water infiltration on slopes can increase stability, but will run-off volumes exacerbating flash floods.				●	●
Understand <b>community and local capacity</b> to manage and deal with flash flood events.		●			
<b>PREPARATION AND DESIGN</b>					
Consider ‘low-cost’ <b>bio-engineered structural measures</b> to reduce or control erosion, protect soil, and stabilize slopes using vegetation or a combination of <b>vegetation and engineering</b> and construction materials		●	●	●	●
Be cognisant that roads and other <b>transport corridors can channel flash floods</b> particularly where the route itself has steep gradient. This can transfer the hazard very quickly across quite large distances to more vulnerable areas. Flash floods volumes are almost certainly beyond the capacity of conventional road drainage.		●		●	●
<b>Bridge scour protection</b> is especially important in high velocity flows.			●	●	●
Gather and use appropriate <b>hydro-met data</b> to support infrastructure design through computational, physical modelling or other technique.				●	●
‘ <b>Hard engineering</b> ’ can reduce flash flooding risk, but can be <b>high cost</b> and have significant operation and maintenance implications.			●	●	●
<b>Ensure debris does not become trapped at bridges and culverts</b> – causing flood water to back-up and placing infrastructure at risk. Higher decks and larger spans, with fewer piers presenting an obstacle to flow would help. Use culvert screens to prevent trash build up (maintenance issue).			●		●
<b>IMPLEMENTATION</b>					
Where risk cannot be mitigated through structural measures, or in addition, use non-structural measures such as <b>early warning systems, education and capacity building</b> .		●			●
<b>Maintenance</b> , such as river bank clearance and channel clearance is important to ensure the flood relief works as originally designed and operated.			●		●

## CASE STUDY 1: Learning to Live with Floods following the 2008 Kosi River Flooding: Kosi River area, India and Nepal

### COASTAL ROADS ON THE FAMILY ISLANDS, BAHAMAS

The Kosi River transports some 120 million cubic metres of sediment annually. However, because of complex and varied precipitation patterns and underlying geology in each of the sub-catchments, there are highly pulsed and variable flows during which time most of the sediment is transported. This sediment partly arises due to incidents such as landslides which block smaller rivers in the middle hills of Nepal. When these are breached they can generate intense sediment laden floods. High sediment flows also arise as a result of earthquakes and glacial lake outburst floods in the Himalayas as well as the general sediment load due to a high rate of erosion upstream particularly in the higher regions of the catchment area.

These natural causes alone, however, are not the sole contributors of flooding events along the Kosi River. Roads, railways, irrigation channels and embankments which block natural patterns of drainage can also accentuate flood events. For example, embankments, while they provide protection to some areas (creating tension between communities), tend to block precipitation from draining into the main stream causing flooding. Moreover where embankments are constructed the only place for sediment deposition is in the river channel itself. This can raise the level of the river bed at rates as high as a metre per decade, reducing river channel capacity, and increasing risk of flooding at times of high flow volume. This has continued so that in some areas the riverbed is 4m above the surrounding lands. Embankments have not controlled flooding but made it worse, as well as created a false sense of security (Shrestha, 2010).

Some of the key issues related to the Kosi flooding and recommendations are highlighted below:

#### POLICIES, INSTITUTIONS AND PROCESSES

**Develop adaptive institutions, improve coordination across borders, and establish local management and control.** Whilst the barrage and upper embankments are located in Nepal, the responsibility to operate and maintain them lies with India. Furthermore the responsibility for the Kosi project lies with the Government of Bihar which must first consult the Government of India, which then consults the Government of Nepal before conducting any infrastructure maintenance. The convoluted institutional mechanism has hindered responsive decision making. Mechanisms for information sharing, decision making, joint control and coordination are poor and need to be improved. However, Shrestha (2010) suggests this extends beyond lack of coordination and information flow and there is a need to address internal and trans-boundary political issues and revisit the now outdated Kosi Treaty.

#### OPERATIONS AND MAINTENANCE

**Improve the monitoring and maintenance of embankments (flood control measures).** According to the flood victims embankments had not been maintained for 7-8 years, and the 2008 flood event was caused by the breach of an un-repaired embankment. Without top down responsibility for shared management and maintenance, investment in building flood controls may not improve flood resilience.

**Improve local awareness and flood preparation.** There were no early warning systems and the possibility of an embankment breach had not been planned for so there was a general lack of preparedness. This also relates to the general level of monitoring and maintenance of embankments, as set out under technical below.



## TECHNICAL

**From flood control to flood resilience.** The intensity of flooding along the Kosi river, when the flow was just 1/7th of the system design flow, was caused by the reliance on flood control measures alone as a flood management strategy. The approach of focusing on engineering solutions, has led to a reliance on structural measures alone for flood control, which has reduced flood resilience. This example highlights a need to shift from a one dimensional approach of 'keeping the water out' through flood controls towards better ongoing maintenance and a holistic long approach of open basin management, or the Dutch concept of 'making room for the river'.

## SOURCES:

Shrestha, R.K., et al. (2010) Institutional dysfunction and challenges in flood control along the transboundary Kosi River: A Case study of the Kosi Flood 2008. In: *Economic & Political Weekly*, 45.2: 45-53. Available from: <http://www.epw.in/special-articles/institutional-dysfunction-and-challenges-flood-control-case-study-kosi-flood-2008.h> [accessed: 20/05/2014]

Moench, M. (2009) Responding to climate and other change processes in complex contexts: Challenges facing development of adaptive policy frameworks in the Ganga Basin. *Technological Forecasting & Social Change* 77 (2010) 975–986. Elsevier.

## CASE STUDY 2: Interagency Performance Evaluation Task Force Post Hurricane Katrina (2005)

After Hurricane Katrina in August 2005 the Corps leadership commissioned an Interagency Performance Evaluation Task Force which was tasked with answering five key questions:

- What was the hurricane protection network in place on August 29th 2005?
- What forces did Hurricane Katrina put on the protection network?
- What were the consequences of this event? and
- What would be the risk and reliability of the protection network on June 1 2006?

It also commissioned a study on the Hurricane Protection Decision Chronology. This was designed to document the chronology of the planning, economic, policy, legislative, institutional and financial decisions that influence the hurricane protections systems of Greater New Orleans. In December, 2005 the National Academy of Engineering/National Research Council Committee on the New Orleans Hurricane Protection projects was set up to provide independent, expert advice to the IPET. The key recommendations that emerged from all three of these studies are highlighted below:

### **POLICIES, INSTITUTIONS AND PROCESSES**

- **Consider relocation as a policy option and ensure that the planning and design of HPS do not encourage settlement in flood prone areas. Voluntary buyouts and relocations of some structures and residents is a politically sensitive issue but can improve safety and reduce flood damage.**

- **'Changes or clarifications to congressional policies and reauthorizations as they relate to large construction projects may be necessary to effectively implement findings of periodic scientific reviews.'** (NRC: 35). The process for incorporating new scientific information on changing environmental conditions or design can be complicated by congressional reauthorization standards. A revision to the standard hurricane standard in 1974 was not incorporated when the project was re-evaluated for fear that the project would need to be re-authorized. This risked delaying the project by several years, as an ongoing prolonged debate on cost sharing rules in Congress meant that no projects had been authorised since 1974.

- **Reporting requirements should ensure that technical experts share all relevant information with decision-makers.** The project record shows that the District of New Orleans knew in general terms of the lessening of project DOP and LOP over time, but the Corps' reporting requirements did not inform the higher authorities or local sponsors that the project if completed would not provide SPH protection. It is important that project evaluation and reporting protocols are in place so that technical experts share all relevant information about project capabilities and limitations with decision makers. Even if no project changes are made this could have an impact on land development and use, wetlands/landscape restoration activities, pumping capability, evacuating planning and emergency response, and special protection of critical infrastructure.

### **OPERATIONS AND MAINTENANCE**

- **Independent bodies should periodically conduct external reviews of large complex projects** -For large complex projects such as the New Orleans hurricane protection system, an independent body should periodically review the design, construction and maintenance should be conducted to ensure that the calculations are reliable, methods are appropriate, designs are safe and any blind spots have been identified. It can also identify politically sensitive issues. 'The absence of a standing, agency-wide process for continuing assessment and reporting of project performance capability left the District to make its own determination as to whether the analytical foundation was adequate for requesting

changes to project designs, and for satisfying higher federal authorities and local sponsors that additional project funding was warranted.’ (Woolley and Shabman, 2007, p. ES-17)

**- Periodically update concepts, methods and data to reflect changing environmental conditions and have a process in place to integrate this information into decision making so infrastructure can continue to meet its performance objectives.** The New Orleans hurricane protection system was designed to a Standard Project Hurricane according to their understanding of hurricanes in the late 1950s. These equations however, were based on storms that preceded Category 3 Hurricane Betsy in 1965, and the strong Category 5 Hurricane Camille in 1969. Most levee heights in New Orleans were adjusted after Betsy but not after Camille’s greater surge heights in Mississippi. After Katrina the standard project hurricane standard was abandoned. Instead, designers created a computerised sample of 152 possible storms, from 25 year events to 5,000 year events and tested each storm along a wide variety of paths, at different forward speeds and accompanied by varying amounts of rainfall. They also modelled the effects of waves accompanying the surge. More than 62,000 model runs were used to develop the overhauled levee system. The levees were rebuilt to block overtopping by surges from a 100 year storm and withstand surges from a 500 year event (overtopping still occurs). Furthermore, their design accounted for South-eastern Louisiana’s sinking soils and projected sea level rise by adding a foot or two increase in the height of the structures.

**Establish a publicly accessible archive of all data, models, model results and model products created from the landmark IPET evaluation to ensure future work builds on these studies.** The NRC report noted that the ‘institutional memory’ of IPET risks being lost as all external experts will return to their respective careers.

#### TECHNICAL – PLANNING AND DESIGN

**- The ITEP recommended that planning and design methodologies need to examine system wide performance where component performance is related to system performance and the consequences of that performance.** A system is only as robust and resilient as its weakest component. In New Orleans the approach was component-performance-based, which made it difficult to examine integrated performance of components. This systems wide approach also needs to be considered in the reconstruction process. The ITEP report noted that the New Orleans metropolitan area was still vulnerable until the remaining sections of the system were upgraded and completed, to match the resilience of the repaired sections. The ITEP report noted that:

“The System did not perform as a system: the hurricane protection in New Orleans and Southeast Louisiana was a system in name only (...). It is important that all components have a common capability based on the character of the hazard they face. Such systems also need redundancy, an ability for a second tier of protection to help compensate for the failure of the first tier. Pumping may be the sole example of some form of redundancy; however, the pumping stations are not designed to operate in major hurricane conditions. The system’s performance was compromised by the incompleteness of the system, the inconsistency in levels of protection, and the lack of redundancy. Incomplete sections of the system resulted in sections with lower protective elevations or transitions between types and levels of protection that were weak spots. Inconsistent levels of protection were caused by differences in the quality of materials used in levees, differences in the conservativeness of floodwall designs, and variations in structure protective elevations due to subsidence and construction below the design intent due to error in interpretation of datums.” (US Army Corps of Engineers (2006) : I-3)

**- Rethink the extent and configuration of High Protection Structures and consider creating a more manageable system of protective structures. Recognise that the risks of levee/floodwall failure can never be reduced to zero and in many cases levees can create catastrophic residual risk if conditions change, they are affected by extreme events or they are not properly maintained.** Before Hurricane Katrina there was ‘undue optimism about the ability of this extensive network (350 miles of protective

structures) to provide reliable flood protection. For this reason the Association of State Floodplain Managers recommended that where levees do exist or are the best option out of carefully considered alternatives, levees should be: '(1) designed to a high flood protection standard; (2) must be frequently and adequately inspected, with all needed maintenance continued and performed (if this does not occur, the levee must be treated as non-existent); (3) used only as a method of last resort for providing a LIMITED means of flood risk reduction for existing development; and (4) are inappropriate as a means of protecting undeveloped land for proposed development' (ASFPM, 2007, all caps in original cited in NRC (2009): 23). Levees should also be designed for planned failure.

- **Reconsider design standards for heavily urbanised areas.** For heavily urbanised regions, the 100 year standard level of protection from flooding is inadequate. For example, a structure located within a special flood hazard area on an NFIP map has a 26% chance of suffering flood damage during a 30 year mortgage (<http://www.fema.gov/faq/faqDetails.do?action=Inut&faqId=1014>). The NRC report noted that: 'The 100-year standard has driven levels of protection below economically optimal levels, has encouraged settlement in areas behind levees, and resulted in losses of life and vast federal expenditures following major flood and hurricane disasters.' (NRC, 2009: 32)

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### CASE STUDY 3: Ecuador - Natural Disaster Management System and the Road Network

Ecuador suffers from numerous mudslide and landslides as well as El Nino, which in 1997-1998 damaged 28% of the transport sector. Roads, contention walls and dikes in Ecuador are poorly designed and constructed, often without technical studies, risk assessments or adequate technical supervision, and fail on a regular basis. A major road in 1999 was closed because of a landslide, cutting of one of two major commuter routes between two cities, and was still closed three years later. A study by the IADB entitled "Ecuador Natural Disaster Management and the Road Network" analysed the various institutional and financial weakness in Ecuador's disaster risk management systems which have created a network of poor quality transport infrastructure. This report proposed a number of recommendations which are summarised and highlighted below:

#### **POLICIES, INSTITUTIONS AND PROCESSES**

- **Eliminate ad hoc institutions, clarify roles and responsibilities and empower the national planning board to prepare, coordinate, enforce and evaluate the DRM plan.** The report noted that Ecuador's system was reactive with a number of ad hoc institutions outside the normal state apparatus dealing with infrastructure and disaster management. These weakened the existing Ministry of Public Works, introduced competition for resources, and created a disjointed system with overlapping functions and little coordination. Regional political struggles in Ecuador were identified as having contributed to the creation and permanence of these ad hoc institutions. Politicians in La Costa region were seen to capitalise on any crisis to create ad hoc institutions in their region that could circumvent the national organisations in la Sierra. The coordination between all these branches was also perceived to be lacking. Each organisation uses and allocates its own resources and makes decisions without coordinating with the others.

- **Continue and deepen the institutional program aimed at improving the Ministry of Public Works' capabilities.** The report noted that the Ministry of Public Works is responsible for procuring its maintenance works but the concessionaires, due to legal problems, have performed no maintenance of rehabilitation. The MOP was observed to be overstaffed, inadequately funded, and with poor capabilities to plan and prioritise.

- **Decouple selection of professionals to manage risk prevention and disaster response from political cycle.** Construction and business groups were seen to be 'closely correlated with political representation', which leads to a poor system for contract supervision and compliance. This fails to encourage good project selection and the incentives for good delivery.

- **Introduce region specific construction code standards for project design, maintenance and rehabilitation and link to supervision and enforcement.** Construction codes were noted to be currently an assimilation and compilation of codes from US, Mexico and Europe. The report recommended implemented area specific codes to reflect the differences in the vulnerability of Ecuador's regions to natural disasters. It was also noted that existing codes are not enforced.

#### **FINANCIAL ARRANGEMENTS AND INCENTIVES**

- **Donors should not provide funds that support a disjointed system and extend the life of ad hoc organisations.** The report identified poor budget discipline and rent seeking as key issues which creates incentives to key technical standards low. In an emergency Ecuador's Finance Ministry may be called upon by the President to transfer funds from other departments to assist in the relief effort. Furthermore, the budget of DRM organisations depends on the level of damage and their bargaining abilities rather than the quality of their prevention and mitigation measures.



- **The report calls for DRM funds to be contingent upon evidence that national and sector plans are in development to encourage greater budget discipline.**

- **The report calls for innovative funding approaches to raise infrastructure quality.** Funding policies were seen to be insufficient and inconsistent, often varying year to year depending on funds and political priorities. Insurance does not cover roads, bridges, railways etc. though by law it must cover airports and seaports. However, the laws regarding insurance are not comprehensive or clear and are rarely enforced.

#### **OPERATIONS AND MAINTENANCE**

- **Establish operational procurement procedures to define the organisations and activities that are eligible for funding, mechanisms for transfer, contracting rules, and stipulate obligations for independent auditing.** Poor procurement practices mired in corruption were reported as a key issue in producing a poor quality of design and construction in Ecuador as firms compete on the basis of the size of kickbacks rather than quality, price and reliability. Moreover, the possibility of further contracts to rehabilitate and repair damaged roads was seen to have introduced perverse incentives at the design and construction stage.

Additional recommendations included:

- **Incorporate communities in the management of tertiary and rural network recovery**

- **Implement incentive contracts and competition for civil works.**

- **Organise a system of pre-negotiated, 'retainer contracts' with private firms to speed recovery**

- **Empower and strengthen technical skills of Mop and provincial governments to define and execute DRM plans**

#### **SOURCE:**

Solberg, S., Hale, D., and Benavides, J. (2003) *Natural Disaster Management and the Road Network in Ecuador: Policy Issues and Recommendations*. Washington, D.C.: Inter-American Development Bank. Available from: <http://www.iadb.org/wmsfiles/products/publications/documents/353002.pdf> [accessed: 20/05/2014]

## CASE STUDY 4: Disaster Risk Reduction and the Road Network, The Philippines

The Philippines is exposed to many natural hazards- typhoons, floods and earthquakes mean the road network also has a high degree of exposure to landslides, road slips, embankment scouring and other geotechnical hazards. Road closures are common, disrupting both the movement of passengers, goods and services, affecting communities and well as negatively impacting on the country's economy and infrastructure.

The road sector was considered a priority for mainstreaming disaster risk reduction by the Regional Consultative Committee (RCC) on Disaster Management. Against this background, a partnership was developed between the Philippines National Disaster Coordinating Council (NDCC) and the Philippines Department of Public Works and Highways to implement DRR on the road network in the Philippines. The partnership was technically supported by the Asian Disaster Preparedness Centre (ADPC) with financial support from UN International Strategy for Disaster Reduction (UN/ISDR) through Swedish International Development Cooperation Agency (SIDA). A Technical Working Group was set-up with multi-agency membership to steer the project and provide the technical inputs needed. The basic approach was to 1) look at the existing procedures followed with regard to DRR and road projects, especially with regard to the feasibility and preliminary stages. 2) analyse the damage to road infrastructure from disasters. 3) Identify steps for incorporating DRR in project developments and 4) Review the future priority needs for road construction projects.

A short report was published about the strategy and actions they have carried out, and are working towards, to achieve these aims. It was entitled "*Towards Mainstreaming Disaster Risk Reduction into the Planning Process of Road Construction*". This case study provides a summary of the main points.

### POLICIES, INSTITUTIONS AND PROCESSES

- **Liaise with a large number of stakeholders, programs, projects and agencies** – The report recognised that mainstreaming DRR concerns into the road sector involves a number of stakeholders and interrelated plans and programs, including: road maintenance investment programs, road improvements, seismic vulnerability assessments, technical assistance for risk assessment and management, monitoring and evaluation of roads, studies on sediment related disaster on national highways, and hazard mapping and assessment for community disaster risk management programs.

- **Improve Environmental Impact Assessments (EIA)** - The previous EIA report structure considers the impact of hazards by defining an "environmentally critical area" of the project site where it is frequently visited by the natural hazards. However, it does not explicitly provide details on how to address natural hazard vulnerability and risks to infrastructure and the consequent impact from its damage or failure.

### FINANCIAL ARRANGEMENTS AND INCENTIVES

- **The report advises that by considering risks at an early stage, there is the potential for cost-savings.** For example, the alignment of roads that avoid areas of high landslide risk may avoid costly stabilisation techniques that would have not otherwise been identified until geotechnical investigations were carried out at the detailed design stage (RCC, 2008). It also points out that national budgets do not always provide funds for surveys and investigations at the feasibility study stage, and it is therefore unusual for disaster risk reduction measures to be incorporated at early stages of project preparation. The cost-benefit analysis was also found not to be comprehensively considering DRR.

## **OPERATIONS AND MAINTENANCE**

- The key recommendation was that the key to successfully integrating disaster risk reduction on road projects lies in the planning phase of the project cycle, which includes project identification and preparation of the feasibility study.

**‘Feasibility reports should include an assessment of the impact of potential disasters’ and ‘DPWH needs to have a standard on project identification and preparation procedures to eliminate quality discrepancies between nationally and externally funded projects and to pave the way for mainstreaming disaster risk reduction in road projects’** - Overall it was found that typically due to lack of funding for construction of national road projects, the Department of Public Works and Highways administers a basic feasibility study, but for foreign-assisted projects the assessment process is more in-depth and extensive. It was also noted that externally funded projects are prepared to higher standards, particularly in relation to environmental assessments (where disaster risk aspects are described if required by the particular agency) and resettlement planning. It was reported that the road studies undertaken did look at hazards, but were primarily limited to protecting the road segments from geological hazards such as landslides and debris, and not comprehensive enough.

### **- Data, monitoring and risk assessment**

It was reported that there was an uneven application of design standards between national and local roads, including an absence of one fixed format for collecting information on damage to roads and bridges from natural hazards. Hydrological data was available, but information was not uniformly processed to allow it to be used in road design (ADPC, 2008) (RCC, 2008). It was additionally noted that is important to benchmark hazard intensities with their return periods/damages, but this was difficult due to low resolution topographic maps, few hazard monitoring stations and a short monitoring period with limited processed data on hazards. The report recommended that the capacity of staff to assess the impact of disasters needs to be increased, particularly at regional and district levels.

### **SOURCE:**

ADPC (2007) *Towards Mainstreaming Disaster Risk Reduction into the Planning Process of Reconstruction*. Available from:

[http://www.adpc.net/v2007/ikm/EVENTS%20AND%20NEWS/NEWS%20ROOM/ Downloads/ 2008/Apr/CaseStudyRoadsPhilippines.pdf](http://www.adpc.net/v2007/ikm/EVENTS%20AND%20NEWS/NEWS%20ROOM/Downloads/2008/Apr/CaseStudyRoadsPhilippines.pdf) [accessed: 07/04/2014]

## CASE STUDY 5: Federal Highway Administration Climate Change Pilot Project

In 2010 the FHWA selected five pilot teams to test its climate change vulnerability asset model. Washington State Department of Transport used a qualitative climate scenario planning approach and facilitated workshops during which participants used asset maps, climate scenarios and local knowledge to assess vulnerability.

### DESCRIPTION

An asset inventory was compiled to help workshop participants identify assets that may be exposed to climate change. Data was collected from different sources, such as asset and maintenance management systems. Climate data was collected from the University of Washington Climate Impacts Group, and used to produce impact maps which communicated historical trends and projections to workshop participants. WSDOT identified climate scenario considering 2, 4 and 6 foot sea level rise, shifts in timing and type of precipitation, temperature extremes, increased severe storms and wildfires

Vulnerability assessment workshops collected and mapped out institutional knowledge about vulnerability. The workshops include 200 participants, including maintenance staff, regional office staff and state ferry, aviation and rail system managers. A GIS specialist overlaid detailed asset inventories with climate impact data and the participants then used a qualitative scoring system to assess assets for criticality and to rate the effect that changes in climate would have on infrastructure. One of WSDOT's best practices for identifying issues and concerns was asking participants 'what keeps you up at night?' and 'what happens if the climate related conditions gets worse?' The advantage of this format was that it used local knowledge and also built key relationships across the department.

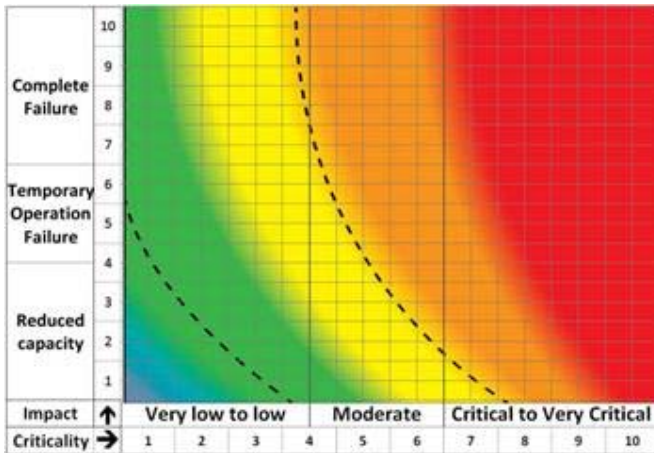


Figure 1: Impact-Asset Criticality Matrix or "Heat Sheet" This is a visual representation of the relationship between relative criticality and potential impacts.

Results were synthesised into a series of maps for each region showing the vulnerability ratings for roads, airports, ferries, railways. The vulnerability ratings were mapped for all modes across the state. Red lines were where one or two areas are vulnerable to catastrophic failure, yellow, where roads are vulnerable to temporary operational failure at one or more locations and green are roads that may experience reduced capacity somewhere along the segment.

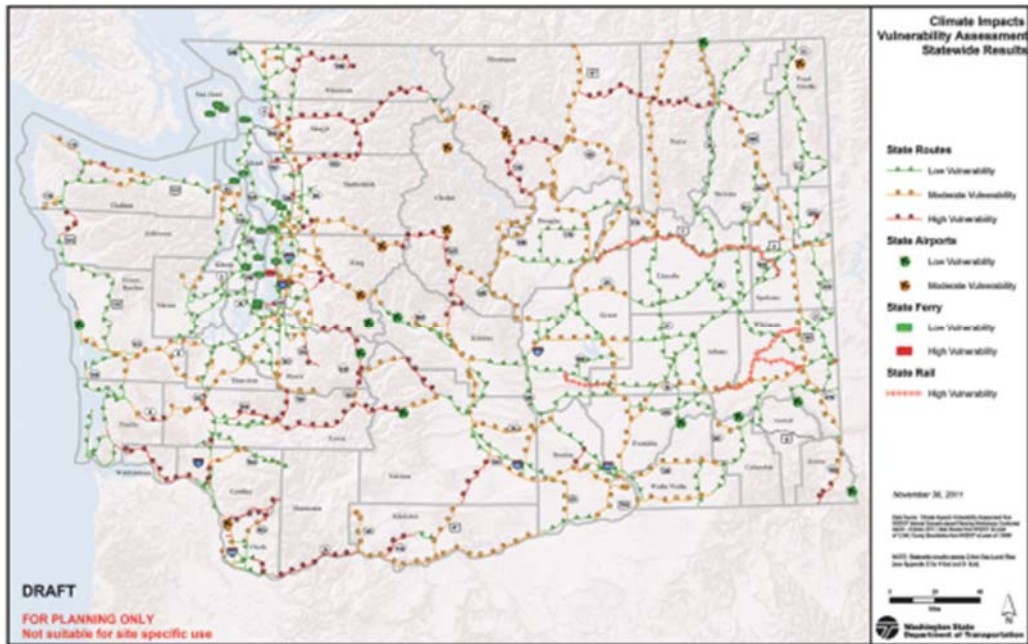


Figure 2: State-wide Climate Vulnerabilities

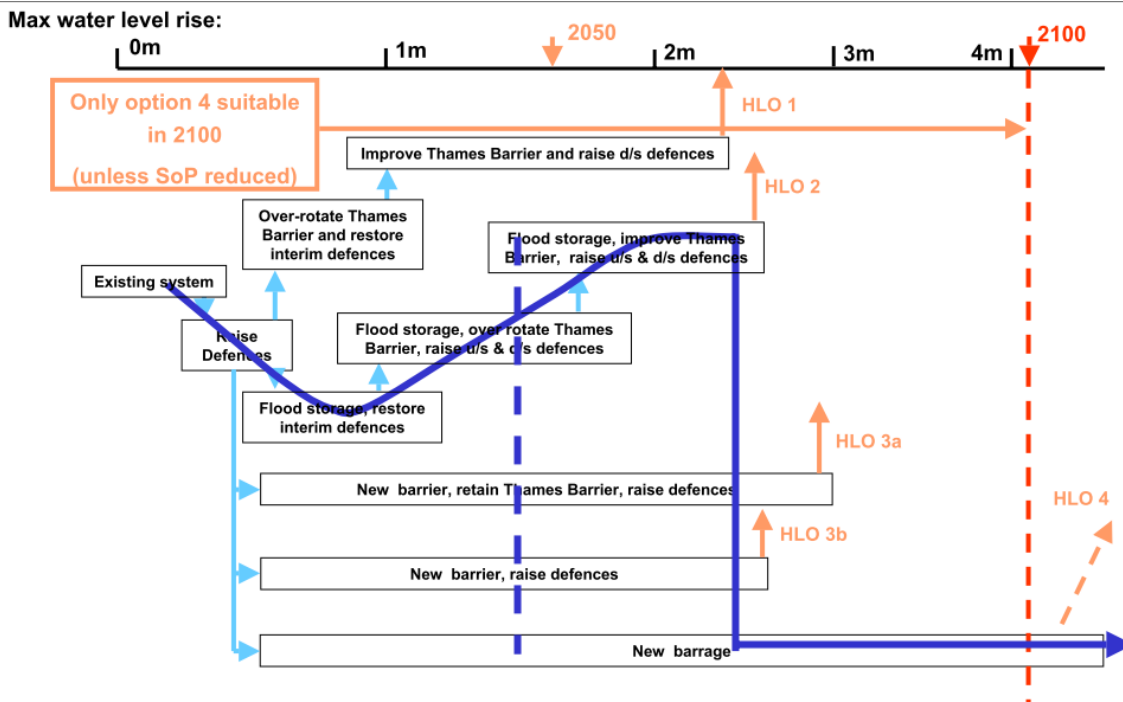
**SOURCE:**

United States Department of Transportation Federal Highway Administration (2010) Climate Change Adaptation Case Studies Washington State Department of Transportation – WSDOT. FHWA-HEP-14-004. Available from: [http://www.fhwa.dot.gov/environment/climate\\_change/adaptation/case\\_studies/washington\\_state/index.cfm](http://www.fhwa.dot.gov/environment/climate_change/adaptation/case_studies/washington_state/index.cfm) [accessed: 20/05/2014]



## CASE STUDY 6: UK Thames Estuary 2100 Flood Risk Management – A Flexible Real Option Approach

The Environment Agency's Thames Estuary 2100 (TE2100) project has developed a strategy for tidal flood risk management up to the year 2100. The range of flood management options presented in the final plan will protect London and the Thames Estuary against sea level rise scenarios and storm surge over the next century, including extreme scenarios. The steps taken are outlined below.



First, the TE2100 project developed a range of climate change scenarios for mean sea level rise and storm surge behaviour and began by assessing the range of responses to the flood risk arising from water level rise. These responses were then gathered into different action portfolios which were assembled into packages to create strategic High Level Options (HLOs), which could deal with different levels of extreme water level rise. These four options were: Traditional Engineering (HLO1), Floodplain Storage (HLO2), New Barrier (with/without Thames Barrier) (HLO3), and New Barrage (HLO4).

Climate changes scenarios were then introduced to see which Options could deal with which scenario, shown in the figure above. All HLOs could deal with water level rise under the 'central' and 'medium high' climate change scenarios, but only HLOs 2, 3 and 4 can deal with a 'High Plus scenario'. Only HLO4 could deal with a 'High Plus Plus' case.

Finally the High Level Options were assembled into schedules of portfolios showing the thresholds these options reached over time. Threshold 1 around 2030-40 was the limit of the existing flood management systems, Threshold 2 around 2070 the limit of the Thames Barrier, Threshold 3, the limit of a modified Thames barrier beyond 210.

Multi criteria analysis was used to outline a range of impacts (direct and indirect) for inclusion in the CBA that was conducted for all High Level Options under a central climate change scenario. The CBA of options was then repeated under different baseline and impact estimates and the option with the highest cost-benefit ratio given current climate change knowledge was chosen. This Option outlines a

series of interventions over time, each of which have estimated lead times that imply decision points at which the individual responses within the wider High Level Option need to be approved.

A monitoring system has been put in place and every 5-10 years the strategy is revisited. If climate change is happening more slowly or quickly decision points for the interventions can be changed to keep benefit-cost relationships close to those set out in the initial appraisal. Also at each review the whole strategy is reappraised in light of new information to see if switching to another High Level Option is recommended by the CBA, for example if climate change has significantly accelerated there may be a case for switching to a tide excluding barrage, HL04.

The TE2100 strategy also safeguards land which may be needed for future flood risk management activities such as new defences, flood storage areas, managed realignment etc.

#### **SOURCES:**

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<http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87898&filetype=pdf> [accessed: 20/05/2014]

## CASE STUDY 7: Flooding Management in the UK – Agricultural Practices and Rural Land Management

The thinking in the UK around flood management has begun to shift towards rural land management and sensitive farming practices. The agricultural sector has a critical role to play in managing and mitigating flooding throughout the system. Farmers have altered the landscape to maximise agricultural production by felling trees, removing hedgerows, engaging in intensive grazing, artificial drainage, and modern farming practices. These have compacted the soil, reduced the capacity of the land to hold water and created conduits for water to run off the surface. Rivers have also been gradually squeezed over the last few hundred years into straight, fast flowing channels to hurry rainwater off agricultural fields. These fast flowing rivers carry silt which causes rivers to clog up and exacerbates flooding downstream, effecting nearby villages, towns and transport infrastructure. It has been calculated that these measures increase the rates of instant run-off from 2% of all the rain that falls on the land to 60% (Environment agency 2012).

Whilst river managers previously thought that it was necessary to straighten, canalise and dredge rivers to enhance their capacity to carry water, this has now been shown to be counterproductive. The Pitt Review, commissioned after the UK's 2007 floods, concluded that "dredging can make the river banks prone to erosion, and hence stimulate a further build-up of silt, exacerbating rather than improving problems with water capacity" (Pitt 2008). Rivers cannot carry all the water that falls during intense periods of rain and measures such as dredging etc. simply increase the rate of flow, moving the flooding from one area to another. The majority must be stored in the soils and on floodplains.

Below are a summary of key recommendations proposed by the Pitt Review and a number of leading flood risk management experts in the UK.

### TECHNICAL – PLANNING AND DESIGN

- **Natural green infrastructure and adaptive management.** The philosophy until now has been to quickly 'get rid of water' but in the UK this is beginning to shift to focusing on rural catchment management solutions that will reduce the peak flow of rivers. There are three general types of measures (Pitt Review 2008):

(1) Water retention through management of infiltration

(2) Provision of storage including wetlands, floodplains, reservoirs, detention basins (dry), retention ponds (wet), grassed swales, porous pavements, soakaways and 'green' roofs.

(3) Slowing floods by managing the hillslope and river conveyance, such as planting woodlands, or restoring watercourses to their natural alignment. Research in the UK on land in Pontbren (mid-Wales) estimated that if all the farmers in the catchment placed tree shelter belts flooding peaks downstream would be reduced by about 29%. Full reforestation would reduce the peaks by about 50% (FRMC: iii). Reintroducing flood plain forests to upland areas slows water as it passes over its irregular surface and is more effective than partly damming streams with felled trees which have unpredictable results as they divert rainfall onto surrounding fields where the water can run off, bypassing bends in the river. Engineers are also reintroducing snags and bends into rivers, which catch the sediment flowing down rivers, as well as reconnecting rivers to the surrounding uninhabited land so they can flood safely and take the speed and energy out of rivers.

### POLICIES, INSTITUTIONS AND PROCESSES

A number of institutional and regulatory barriers still exist to promoting rural land management. Tree planting grants in Wales have stopped (Monbiot 2014) and the Common Agricultural Policy states that to receive a single farm payment (the biggest component of farm subsidies), the land has to be free

of 'unwanted vegetation' (Monbiot 2014) otherwise it is not eligible. These subsidy rules have unwittingly resulted in the mass clearance of vegetation and exacerbated flooding. At the same time, grants to clear land have risen in the UK, and farmers now receive extra payments to farm at the top of watersheds. In the UK the green group WWF has said that farmers should only get subsidies if they agree to create small floods on their own land to avoid wider flooding in towns and villages.

Farmers have suggested that instead of making grants conditional on river management, farmers should be given extra financial incentives. Whilst farmers can already get extra EU grants to hold water on their land experts say subsidies are harder to obtain. Furthermore research (FMRC 2008) has estimated that all farmers in a catchment area must become involved in river management to significantly reduce peak flows, and opt in financial incentives tend to be less effective in inducing behaviour change than conditionalities.

#### SOURCES:

Pitt, M. (2008) *The Pitt Review: Learning Lessons from the 2007 Floods*. Available from: [http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pitt-review/thepittreview/final\\_report.html](http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pitt-review/thepittreview/final_report.html) [accessed: 20/05/2014]

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Monbiot, G. (13/01/2014) Drowning in Money: The untold story of the crazy public spending that makes flooding inevitable. *The Guardian*, (01/2014) [Online] Available from: <http://www.theguardian.com/commentisfree/2014/jan/13/flooding-public-spending-britain-europe-policies-homes> [accessed: 20/05/2014]

Flood Risk Management Research Consortium (2008) *Impacts of Upland Land Management on Flood Risk: Multi-Scale Modelling Methodology and Results from the Pontbren Experiment*. FRMRC Research Report UR16 [Online]. Available from: [http://nora.nerc.ac.uk/5890/1/ur16\\_impacts\\_upland\\_land\\_management\\_wp2\\_2\\_v1\\_0.pdf](http://nora.nerc.ac.uk/5890/1/ur16_impacts_upland_land_management_wp2_2_v1_0.pdf) [accessed: 20/05/2014]

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## CASE STUDY 8: Partial Infrastructure Failure following Severe Storm Event tracked to Maintenance Deficit: Balcombe Tunnel, West Sussex, UK

In the UK in 2011, an emergency inspection showed partial collapse of the steel structure fixed to the underside of rail tunnel in Balcombe, on the main train line from London to the South Coast of the UK. This brief case study highlights the value and critical importance of periodic inspection and maintenance regimes. The failure occurred following a period of prolonged rainfall and flooding, but a higher standard of infrastructure maintenance could have enabled this infrastructure to be resilient at this time.

### TECHNICAL – PLANNING AND DESIGN

**Technical failure scenario** - The tunnel lining attached to the brick tunnel roof became detached following the failure of some of the supporting anchors (20mm diameter threaded stainless steel anchor studs fixed with polyester resin into holes drilled in the tunnel's brick lining). Further failure could have had catastrophic consequences for trains passing through the tunnel. On the steel structure 18 studs (5%) were found to be missing and a further five studs were loose. Although the underlying defect was known about, it was not addressed. Had not the crew of an engineering train passing through and noticed the defect, a much more serious event could have occurred. The subsequent investigation found that the resins used were not compatible with the brickwork, with damp and shrinkage exacerbating the situation.

### POLICIES, INSTITUTIONS AND PROCESSES

**Need for Robust Inspection and Maintenance Regime** - A number of other causal factors were also identified including those responsible for the maintenance of the tunnel failing to recognise the significance of the missing studs identified before the partial collapse, despite numerous early indicators of the error. Information on the defect was also not shared and addressed in a systematic way and an administrative error recorded that the defect had been addressed when it had not. There was also confusion when identifying and communicating the specific defect area, partially because the tunnel chainage markers were incorrect in places.

The above case study is summarised from RAIB (2013).

#### SOURCE:

Rail Accident Investigation Branch (RAIB) (2013) *Rail Accident Report: Partial failure of a structure inside Balcombe Tunnel, West Sussex, 23 September 2011*. Rail Accident Investigation Branch, Department for Transport. Report Ref: Report 13/2013, August 2013. Available from: [http://www.raib.gov.uk/cms\\_resources.cfm?file=/130815\\_R132013\\_Balcombe\\_Tunnel.pdf](http://www.raib.gov.uk/cms_resources.cfm?file=/130815_R132013_Balcombe_Tunnel.pdf) [accessed: 20/05/2014]



## CASE STUDY 9: Local Solutions and Alternative Materials to Increase Resilience of Low Volume Roads: Bagomoyo and Lawate-Kibongto Roads, Tanzania

The African Community Access Programme (ACAP) is a research project working to improve the resilience of gravel or compacted earth roads. Such roads often become impassable or repeatedly washed away following heavy rainfall. While this case study focuses on the 90% of Tanzania's 91,000 km of roads which are unpaved the lessons learnt will equally apply to the majority of rural roads in sub-Saharan Africa, and others worldwide, which are of similar construction.

The approach taken by ACAP is to provide technical support and guidance to make longer-lasting repairs with local materials and labour. This avoids the need for the main road network to be upgraded or strengthened using imported aggregate, which is expensive, not least because of the transport distances required.



Rural concrete slabs undertaken as part of Dfid's AFCAP (African Community Access Programme). Source: Roughton



Geocells being installed as part of DFID's AFCAP (African Community Access Programme). Source: Roughton

The main problem encountered was that most road specifications published are for conventional highway construction for heavily trafficked highways. These generally restrict the use of locally sourced marginal materials which increases costs and make low volume road upgrades uneconomical. It can also dissuade investment in routine and periodic maintenance.

This project produced different material specifications to produce 'environmentally optimised' road designs that utilise materials that are, in theory, inferior to crushed stone. However, for low volume roads, such as noted below the key design feature is not to accommodate lots of heavy vehicles, but to survive through heavy rainfall and flooding events.

### TECHNICAL – PLANNING AND DESIGN

#### -Targeted isolated problem sections on two roads through the use of geocell materials in 'soft spots'

The Bagomoyo road is rolling in nature and is for the most part sandy earth, but has some black cotton soil sections which become very weak when wet. As a result, the road tended to become impassable due to flooding of the black soil, which turned into a sticky mud during the rainy season. The road was reconstructed using strips of concrete in each wheel path. The concrete was infilled into geocells and various type of bituminous surface dressing and slurry seal then applied.

The Lawate-Kibongoto road in the district of Siha contains many steep sections and is constructed from local red clay soils, which becomes very slippery when wet. In some places even four-wheel drive vehicles cannot climb the hills after rains. This road was reconstructed using lightly reinforced and unreinforced concrete slabs and paving blocks, as well as a double surface dressing and concrete strips and geocells like those used at Bagomoyo.

Combining innovative approaches and locally focused 'appropriate technologies' removes the requirement for costly upgrading of the majority of the roads. This will avoid the need for roads to be frequently re-gravelled or rebuilt after heavy rains. At both sites the designs utilised materials such as cement and bituminous slurry seal which are not available in many places, and the plastics geocells were imported from South Africa, however, the road construction was able to be delivered using a labour based approach.

#### **OPERATIONS AND MAINTENANCE**

This approach used **labour based construction methods** using predominantly locally sourced materials

Both of these two roads have been monitored to see the performance of these alternative pavement techniques, particularly after heavy rainfall. Design manuals have been published for engineers in Ethiopia and Malawi, and further individual projects are working towards similar outputs for Kenya, South Sudan, Mozambique, the Democratic Republic of Congo and Tanzania.

This project employed Roughton as the consulting engineer, and was funded by the UK Department for International Development (DFID).

#### **SOURCE:**

Masters, J. (13/02/2014) Cure for Africa's Rustic Roads. *New Civil Engineer*. [Online] Available from: <http://www.nce.co.uk/features/transport/cure-for-africas-rustic-roads/8658753.article>. [accessed: 25/03/2014]

## CASE STUDY 10: Upgrading Bridge Design to increase Disaster Resilience: Guadalcanal, Solomon Islands.

The Solomon Islands have regularly experienced climate-related extreme events; including tropical cyclone-related heavy rains, storms and coastal storm surges; which have caused significant economic losses as well as loss of lives. Guadalcanal, the largest of six major islands of the Solomon group, experienced around 40 different disaster events between 1950 and 2009. In response, the Solomon Islands Government was supported by donors to rehabilitate the roads to be able to withstand a higher category of weather event. This focused on repair and improvement to the White River to Naro Hill Road in North-western Guadalcanal, particularly due to the impact of debris flows and landslides.



Flooding aftermath in USA (Des Moines, Iowa).  
Source regan76, Creative Commons License. Date: June 23, 2008.

### TECHNICAL – PLANNING AND DESIGN

**Upgrading the threshold capacity of bridges** - This Solomon Islands Road Improvement Programme (SIRIP2) sub-project upgraded the threshold capacity of the bridge structures, increasing the bridge design to a high-level bridge (1.5 m above the Q100 level) to allow for debris to pass under the bridge deck. The debris catcher (to catch debris flows and slides, which often result from landslides) was also designed specifically for the Tamboko site.

This solution followed an assessment of the impacts of debris flow on main bridges as part of engineering adaptation to climate proof infrastructure. For example, the Tamboko Bridge was originally designed as a low-level bridge at Q10 level, with upstream river training and debris catcher. However, following the 2010 flooding events, the bridge design was changed to a high-level bridge, (1.5 m above the Q100 level) to allow for debris to pass under the bridge deck. The high level bridge also has 30-metre spans so that there are significantly fewer obstructions to the flow. The debris catcher was also designed specifically for the Tamboko site due to the high load of debris that occurred during the 2009 and 2010 flood events. Such an adaptive approach to increase the threshold capacity of these key structures following the 2010 flooding experience was possible.

### SOURCE:

Lal, P.M. and Thurairajal, V. (Nov 2011) *Making informed adaptation choices: A case study of climate proofing road infrastructure in the Solomon Islands*. Available from: <http://www.climatechange.gov.au/climate-change/grants/pacific-adaptation-strategy-assistance-program/making-informed-adaptation-choices-case-study-climate-proofing-road-infrastructure-solomon-islands> [accessed: 20/05/2014]

## CASE STUDY 11: Protection of Bridge Piers from Failure to Scour: Lancashire, UK

Lower Ashenbottom Viaduct is located on the preserved East Lancashire Railway near Rawtenstall in Lancashire. In June 2002 the central pier of the viaduct carrying the railway over the River Irwell partially collapsed, probably due to scour caused by debris collecting against the middle pier.



Flood Damage Burway Bridge over the River Corve after the floods (UK). Source: DI Wyman and is licensed for reuse under the [Creative Commons Attribution-Share Alike 2.0 license](#). Date 3 July 2007

London Underground (LU) is in the process of installing scour protection for four of the bridges identified as being at the highest risk of scour. The first is a Victorian brick arch structure (Underbridge MR80) over the River Gade in North London, which was originally constructed in 1887.

Salmonberry Bridge & Port of Tillamook Bay Railroad damaged during the Dec. 3rd 2007 Flood: Lower Nehalem River Road Confluence of the Salmonberry River & the Nehalem River, Salmonberry Oregon. Source: Chris Updegrave, Creative Commons License, February 09, 2008.

### TECHNICAL – PLANNING AND DESIGN

In Lancashire, **debris capture was key to reducing scour damage**. Calculations indicated that scour resulting from recent flood flow (25-50 year return period, June 2002) without any debris did not exceed the estimated foundation depth and no other structures nearby were damaged due to the same flood event. Flood levels did not reach the bridge deck hence any possibility of deck flotation and loss of support to the pier from the dead load could be discounted. Further analysis showed that debris collection on the central pier (especially a large tree trunk) would have doubled scour depths through creating additional turbulence and enhanced local flow velocities. This example demonstrates how the failure to maintain the flow of a water-course, and undertake maintenance – or otherwise prevent debris collecting at key locations – can significantly reduce flood resilience.

In London a **Feasibility Study identified the most appropriate scour protection** solutions. This included an intrusive survey to determine the existing geotechnical parameters and an ecological survey to minimise construction impacts. In this case, the preferred solution was to install steel sheet piles upstream and downstream, construct a concrete invert in the river between them, and place precast concrete blocks downstream of the concrete invert to prevent scour holes forming.

### SOURCES:

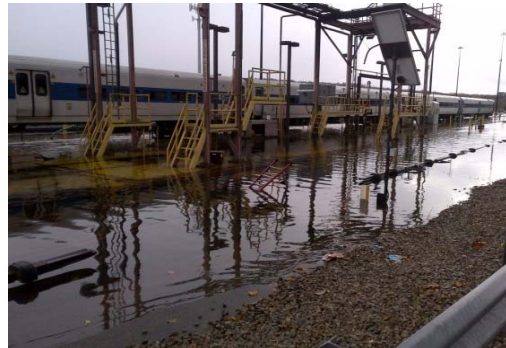
Benn, J. (2013) Railway Bridge Failure during Flood in the UK and Ireland: Learning from the Past In: [Proceedings of the ICE - Forensic Engineering, Volume 166 \(Issue 4\)](#), 01 November 2013), pp. 163 – 170 [accessed: 20/05/2014]

Cole, M. (2014) *London Underground Bridges, Shield of Steel*. Available from: <http://www.nce.co.uk/home/transport/london-underground-bridges-shield-of-steel/8659312.article> [accessed: 20/05/2014]



## CASE STUDY 12: Public Transport Infrastructure Resilience to Major Flooding Events, New York, USA

The impact of Hurricane Irene (2011) on the rail infrastructure, low lying areas and subway system in New York City shows how public transport infrastructure that is of strategic importance to the capital city's economy can be impacted by severe flood events. Recent experiences of flooding in New York have resulted in a number of improvements to the resilience of the transport infrastructure being proposed, as set out below.



Flooding and damage to Metro-North's system -- in the aftermath of Hurricane Sandy - to the bridge and south yard at Harmon. Souce: MTA. Creative Commons License. Date: October 30, 2012

### TECHNICAL – PLANNING AND DESIGN

#### - Protection of Underground Tunnels and Terminals from flash flooding:

Flooding has forced the closure of New York's subway a few times in the past decade. This includes heavy rain (2 inches falling in an hour) in 2004 and a flash flood of 3.5 inches in August 2007. This led to \$30 million worth of flood mitigation projects including the installation of valves to keep discharged water from re-entering the subway system, raising subway station entrances, and improved pumping and sewer system capacity. These measures were suggested in the New York City Department of Design and Construction (2005) but alone have proved insufficient to prevent flooding, such as by Superstorm Sandy (2012). As a result, other approaches are being investigated. Other recommendations (NYCDDC, 2005) include: Installing waterproof, vertical roll-down doors at the foot of subway stair entrances, installing mechanical below-grade vent closures to prevent water from entering through ventilation shafts; protection to seal off electrical equipment from flood risk; and using inflatable plugs/bladders to keep flood waters out of tunnel entrances – which is discussed below.

- The concept of an **Emergency Tunnel Closure** is being investigated by the Resilient Tunnel Project. This is an initiative being developed by the Pacific Northwest National Laboratory, West Virginia University, and ILC Dover for the US government to prevent and contain tunnel flooding (Ahlers, 2012). The concept is to install an inflatable cylinder which can be activated and inflate in minutes to plug tunnels to protect them from flooding. The design allows this solution to be deployed in different tunnel cross-sections such as where there are platforms, lights, tracks and other equipment. This approach is being evaluated to see in what instances it is more cost-effective than retrofit of existing tunnels.

- **Protect above ground transit systems:** Both Hurricane Irene (2011) and Superstorm Sandy (2012) demonstrated how commuter rail service on Long Island and low-lying segments of the Metro-North system are vulnerable to severe events. This vulnerability included key facilities such as depots, signalling systems and electricity substations – with impacts including flooding and associated corrosive damage from prolonged salt water exposure, and in some cases rail track being washed away. Recommended flood mitigation measures include:

- Constructing drainage improvements along railroad rights-of-way and at rail/bus depots, including culverts which channel water underneath the railway. Retaining walls should also be constructed, where appropriate, to protect the railway.

- Installing aluminum dam doors at depots that house buses and trains in low-lying areas prone to flooding (e.g., Zones A, B and C).
- Relocating sensitive equipment from the basement and first floor to higher floors or to the roof.
- Installing new, permanent, high capacity pump equipment.
- Reinforcing water-penetration points in depots and stations, such as windows, doors or cracks in walls.

**- Upgrade pumps in flood prone areas**

In addition to pursuing new flood mitigation measures, improvements to existing pumping capacity at tunnels and other below-grade facilities should be implemented. This is essential to limiting water exposure and ensuring rapid restoration of service. Improvements should include:

- Installing new, higher-capacity discharge lines at points of water accumulation.
- Upsizing existing fixed pumps.
- Installing adequate back-up power sources to ensure that pumps continue to operate even in the event of a localized power outage.
- Ensuring the availability of high capacity mobile pumps to respond to unpredictable flooding situations in a variety of locations.

**SOURCES:**

New York City Department of Design and Construction (2005) *High Performance Infrastructure Guidelines*. Available from: <http://www.nyc.gov/html/ddc/downloads/pdf/hpig.pdf> [accessed: 08/04/2014]

Ahlers, M. (01 Nov, 2012) "*Huge Plugs could have Spared Subways from Flooding, Developers Say.*" [Online] CNN News. Available from: <http://edition.cnn.com/2012/10/31/us/new-york-subway-plugs/index.html> [accessed: 20/05/2014]



## CASE STUDY 13: Bioengineering (Fascines) for Effective Road Maintenance: West Coast Road, St Lucia

Since the mid-1980s the West Coast Road (WCR) has been undergoing improvements, principally widening. Soil erosion and slope stabilisation are significant problems along the WCR. The predominant erosion process is surface erosion on the cut slopes, fill slopes and soil disposal areas with a few pockets where weaker materials had failed in shallow slumps.

Since this time significant bioengineering works have been undertaken to address the particular nature of the erosion problems for different rock and soil types. In the case of slopes characterised by a matrix of volcanic boulders and clay, soil erosion was more pronounced and minor gullies had been formed on some of these cut slopes. There were also sections of the road where residual volcanic clays overlaying unweathered clay materials had become saturated and then failed as slumps.

A variety of bioengineering techniques had been used on fill slopes and soil disposal sites. These included fascines and live mini check dams of *G.sepium*, as well as extensive use of *Bambusa vulgaris*, *V.Zizanioides* and *P.purpureum*. For example, 25-45 degree slopes were extensively planted with *Vetiveria zizanioides* and fascines of *Pennisetum purpureum* which were held in place by pegs of *Gliricidia sepium*. At the base of the slope and above the drain, dry stone boulder toe walls had been constructed with *V.zizanioides* planted between the boulders. Other bioengineering techniques used include planting a wide variety of grass, shrub and tree species.

Details on the areas where fascines should be used, the specific construction methods, and materials used are presented below.

### TECHNICAL – PLANNING AND DESIGN

**Fascines** - A fascine is created to form a dense hedge on the contour of the slope from materials which have the capacity to propagate from horizontally placed hardwood cuttings. Fascines are able to withstand small surface slope movements and are strong in tension across the slope.

#### Area of use

1. Strengthen the sides of gullies and vulnerable areas below culvert outfalls
2. Protect drains from becoming blocked by small boulders from above the slope
3. Rehabilitate spoil disposal sites
4. Stabilise fill slopes
5. Check shallow surface movements of < 300mm depth on cut slopes in soft materials

#### Site Condition

1. *G.sepium* fascines are most effective on well drained granular soils or loosely compacted debris materials
2. Use on slope gradients up to 30 degrees. Can be constructed on steeper slopes but it is undesirable to have unmanaged trees on very steep slopes due to the extra surcharge on the slope and risk of topping. If used on steeper slopes the fascine should be coppiced or pollarded
3. *Pennisetum purpureum* (Elephant grass) fascines can be used on steep slopes up to 45 degree

#### Materials

*Gliricidia* cutting diam. 60-120mm, length 1-2m, ring-barked at intervals of 300-500mm and 4m of *Gliricidia* cutting required per running meter of trench

#### Construction steps

1. Line out a contour along the slope.
2. Prepare cuttings of *G.sepium* (see specification D). Ring-bark at intervals of 300-500mm to stimulate rooting along its length. Prepare bundles of 4-5 and keep in a cool area until required.
3. Prepare a 200mm deep trench on the contour of the slope.
4. To conserve soil moisture, do not open up long areas of the trench before the cuttings are ready to be laid along the contour.
5. Place the bundles of cuttings into the trench. Ensure that the separate bundles of cutting overlap.
6. Roots will develop from the base end of each cutting and also where the cutting has been ring-barked. In order to make the fascine as strong as possible these points of most vigorous rooting should not overlap.
7. Cover the cuttings with a maximum of 100mm of soil.

**SOURCE:**

This case study draws together a case study and technical details from Clark, J., and Hellin, J. (1996) *Bio-engineering for effective road maintenance in the Caribbean*. Natural Resources Institute (NRI), Chatham, UK.

Available from: <http://www.nri.org/publications/cat/landwater.htm> [accessed: 20/05/2014]

## CASE STUDY 14: Embankment Slope Stabilisation and Drainage using Cellular Geotextile: Junction 16-23 M25 Widening Project, United Kingdom

The construction of the M25 widening project (Junctions 16 to 23 and Junctions 27 to 30 in July 2009) was constructed to be resilient to potential slope erosion. The construction of embankments used a geotextile structure as a cost-effective way to help prevent erosion of the motorway's steep embankments, ensuring maximum stability with minimal maintenance.

The details and advantages of this technique are highlighted below.



Source: Terram (PGI).

### TECHNICAL – PLANNING AND DESIGN

**A honeycombed geotextile system was installed on the surface of the constructed embankment.**

Once secured in place with pins, the cells were filled with a layer of top soil which was then hydro-seeded. The strong and flexible cellular structure of the geotextile is designed to prevent the movement of the top soil layer, while allowing surface drainage needed for vegetation growth.

This combined function of enabling vegetation growth while maximising stability allowed the geotextile to support the establishment of vegetation cover acting as natural anchor and protecting the embankment surface from weather erosion.

Approximately 1,800m<sup>2</sup> of geotextile was installed along the 6m high embankments. The geotextile used in this example, Terram 1B1, consists of an extruded polymer grid core with a non-woven geotextile filter thermally bonded on both sides. The core acts a vertical channel, directing excess ground water down into the main drainage system, while the filters allow the water to pass into the core but prevent soil from washing through. This Design Build Finance and Operate (DBFO) contract was awarded by the Highways Agency to Connect Plus and built by the contractors Skanska and Balfour Beatty.

### SOURCE:

Terram (2014) Case Study: Geocells used to prevent embankment erosion: Slope Stabilisation and Drainage for the M25. Published at <http://www.terram.com/projects/slope-stabilisation-and-drainage-for-m25.html> [accessed: 20/05/2014]

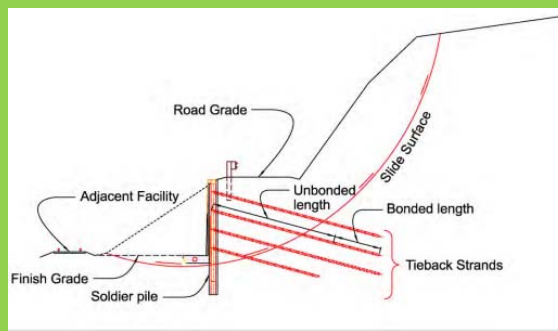
## CASE STUDY 15: Reducing Landslide and Rockfall Risk due to Cascadia Earthquake and Tsunami Events: Oregon, US

Oregon, USA has been recognized as an active fault in the Cascadia subduction zone, which poses a major geological hazard. Recent research by the U.S. Geological Survey (USGS) has shown that seismogenic landslides (that is, new slides initiated by earthquakes) tend to move a few inches to a few feet, while existing slides reactivated by earthquakes are more likely to move several yards, so it is important to focus on existing failures. At the time of writing there were 526 known unstable slopes directly affect US highway 101 alone. These could be reactivated and fail catastrophically during a primary earthquake or following the resulting tsunami, or be destabilized to varying degrees, which could then be affected by aftershocks and restrict rescue and recovery efforts. In 2013, the Oregon Seismic Safety Policy Advisory Commission proposed new steps to improve resilience to the next big disaster event. This Oregon Resilience Plan emphasizes the resilient physical infrastructure needed to improve the resilience of infrastructure, communities, and the economy.

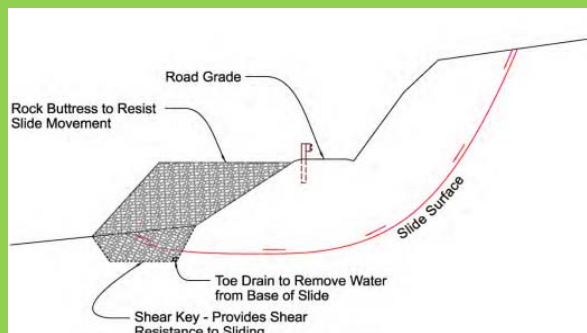
The following photos and diagrams describe some of the most common slope failure modes from landslides and rockfalls and the possible mitigation strategies for that type of failure. All are reproduced with permission from ODOT.

### TECHNICAL – PLANNING AND DESIGN

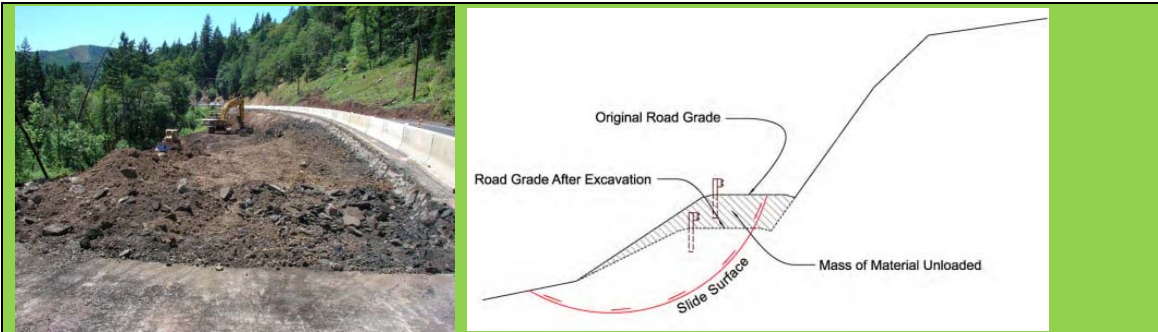
#### 1. Structural mitigation of a landslide: constructing a retaining wall



#### 2. Stabilising a landslide by constructing a shear key and buttress



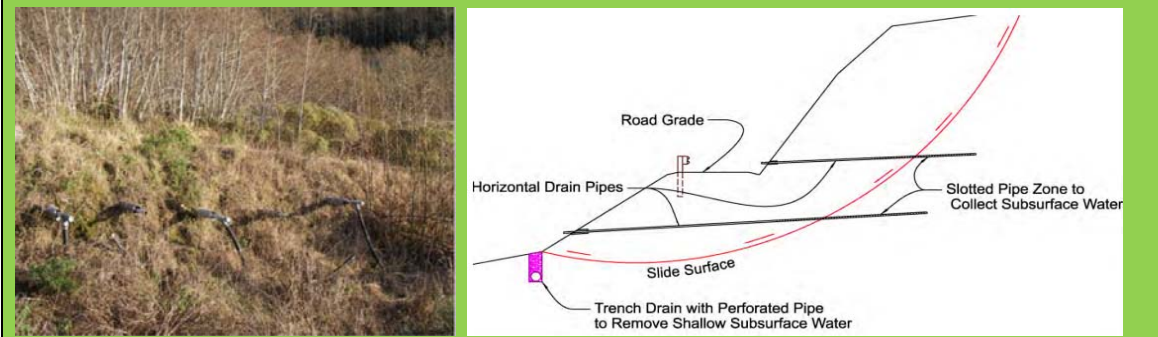
#### 3. Stabilising a landslide by the Unloading method



**4. Flattening the slope decreases the “driving force” of an active slide**



**5. Drainage is one of the most cost-effective methods of landslide mitigation**



**SOURCES:**

Oregon Seismic Safety Policy Advisory Commission (OSSPAC) (2013) *The Oregon Resilience Plan: Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami - Report to the 77<sup>th</sup> Legislative Assembly*. OSSPAC . Salem, Oregon (02/2013)  
 Available from: [http://www.oregon.gov/OMD/OEM/ossprac/docs/Oregon\\_Resilience\\_Plan\\_Final.pdf](http://www.oregon.gov/OMD/OEM/ossprac/docs/Oregon_Resilience_Plan_Final.pdf)  
 [accessed: 20/05/2014]



## CASE STUDY 16: Sea Wall Reconstruction following Hurricane Floyd (1999) Coast Roads on the Family Islands, Bahamas

In 1999 Hurricane Floyd, a Category 4 (in fact wind speeds were just 2mph short of category 5) hurricane traversed the Bahamian Islands at peak strength causing significant damage to coastal roads and wooden jetties used to access water taxis and fishing boats plying between the various islands. The majority of the Bahamian Islands are low lying coral islands rising at the coast to just a few metres above sea level. To design new sea walls that would not be overtopped by wave action and sea surges associated with future hurricanes would have been both expensive and visually intrusive. The latter was also considered undesirable in a tourist location. Alternative innovative solutions were needed to address these constraints. Of the solutions investigated two were carried forward to detailed design and construction.



In choosing the solutions, note was taken of the fact that during the *most extreme weather events*, namely further hurricanes, residents would be advised to remain indoors and not drive their cars. Therefore vehicle traffic on the coast roads would be minimal. It was decided that the walls should be designed for safe failure and to deconstruct under continuous and prolonged overtopping. The defining features and advantages of this design are highlighted below. Bahamas Castellated Sea Wall, Source: IMC Worldwide

### TECHNICAL – PLANNING AND DESIGN

- **The wall would be over topped by wave action.** The top level of the blocks was coincident with the new level of the adjoining road. The joint between the road and the blocks would be sealed by concrete so that water could not penetrate behind the blocks. Receding flood waters would not be contained behind the wall and thereby not impose an overturning force at the top of the structure.

- **The wall was designed to deconstruct.** Under continuous and prolonged overtopping under an extreme event a loss of part or whole of the wall was accepted. This design was already proven: following Hurricane Frances in 2004 a number of the walls were locally damaged but the blocks were readily recoverable from the beach and available for a wall's reconstruction. Therefore, the blocks were sized to have sufficient mass to resist wave forces without significant damage should they be dislodged and submerged. They would then likely remain on the beach until the weather event subsided. The mass of the wall blocks was also sized to ensure it was able to be lifted by the typical construction equipment available on the islands.

- **Castellated Wall Upstands.** These are typical RC retaining structures bedded on the rock. The tops of the walls extended above the road level behind the wall. Again the overall height was insufficient to prevent wave overtopping during the more extreme weather events. Raising the walls was not an economic or environmental solution. To restrict the inevitable but infrequent damage concrete slabs were used behind the walls. To reduce the overturning effects of flood water retained behind the wall castellations were introduced in the wall upstand to break up the wave action yet allow the waters to recede readily from behind the walls used.

### SOURCE:

White, J.A.S. (2001) Hurricane Floyd Reconstruction. WSPimc.

## CASE STUDY 17: Reconstruction of Timber Jetties following Hurricane Floyd (1999): Family Islands, Bahamas

In 1999 Hurricane Floyd, a Category 4 (in fact wind speeds were just 2mph short of category 5) hurricane traversed the Bahamian Islands at peak strength causing significant damage occurred to coastal roads and wooden jetties used to access water taxis and fishing boats plying between the various islands. All piled and decked jetties lost the majority of their timber decking and had the timber piles dislodged. Video footage of the destruction of one jetty shows the waves surging up underneath and either “popping” the planks into the air or physically lifting sections that were well fixed, thus lifting the piles. Until the timber decking gave way, vertical uplift loads had been imparted to the piles, which caused them to be loosened or completely lifted from the sea bed, resulting in further damage to the remaining structure of the jetty. One option could have been to adopt a heavier construction or different materials which would have increased resilience – but this approach was considered to be neither economic nor sustainable.



Photos: Bahamas Timber Jetties, after Hurricane Floyd: Source: IMC Worldwide

An alternative approach was utilised whereby the existing construction methods could be maintained, and at a cheaper cost. The defining features of this resilient construction method are highlighted below.

### TECHNICAL – PLANNING AND DESIGN

- **The timber decking was designed as drop in removable panels.** These drop in panels did not transmit the wave impact forces to the surrounding structure and hence to the piles. However, to avoid the panels being dislodged by larger waves that were not associated with extreme weather events some form of breakaway fitting had to be designed to retain the panels in place until such time as the forces imposed on the panels could result in consequential damage to the surrounding structure. A simple metal strip fuse was bolted at points around the underside of the drop in panel to retain it in place under normal load conditions. The fuse had to be designed to fail at a suitable load. The design used was a simple galvanised steel strip designed to fail in bending at a defined load equivalent to what was deemed an unacceptable uplift force.

The photograph (below on left-side) illustrates that “Lift-out” deck panels removed and stacked ready to be stored safely ashore. The photograph (below on the right-side) shows that fixed deck panels at pile locations for stability with a typical “pop-out”/“lift-out” panel placed ready for fixing.



Photos: Bahamas Timber Jetties, after reconstruction (Source: IMC Worldwide)

#### **OPERATIONS AND MAINTENANCE**

- **Capacity Building.** One concern was future replacement of the fuses. While the Works Department knew this was important there still a concern that this information might be lost by changing personnel and/or not cascade down to the relevant persons in charge on the islands. Without this retained institutional memory 'failure' of the panels could lead to engineers or others "making sure it does not happen again" by fixing the panels rigidly in place or using unsuitable stronger fuses. Sufficient attention and funding for capacity building is therefore crucial for ongoing resilience.

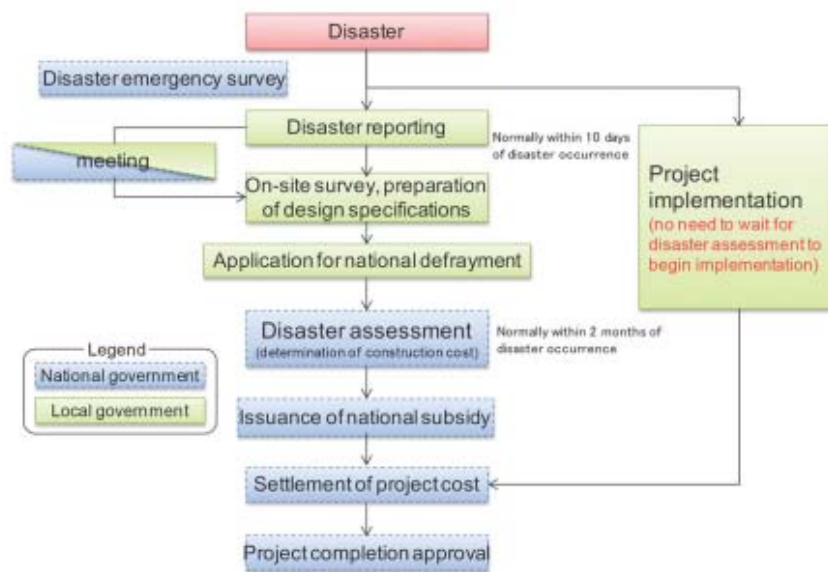
**Post-disaster performance of drop in panels:** In 2004, around three years after these jetties were reconstructed, as set out below, the Bahamas was again hit by Hurricane Frances, a Category 4 hurricane. Many of the jetties lost their drop in panels, but these were recovered. The jetties were quickly restored by re-inserting the salvaged panels and replacing those lost using locally available materials, which was particularly important on the more remote islands.

#### **SOURCE:**

White, J.A.S. (2001-03) Hurricane Floyd Reconstruction. WSPimc.

## CASE STUDY 18: Fast Recovery and Resilient Rail Reconstruction following Great East Japan Earthquake (2011): Japan

The reconstruction of Japan's transport infrastructure after the Great East Japan Earthquake was more efficient and rapid than the Kobe earthquake in 1995. Following the 1995 quake it took over a year and a half for highway reconstruction and 82 days for the bullet train infrastructure to be repaired. In contrast, the 2011 damage to Japan's road network was limited because of seismic retrofitting and rehabilitation work. The main highways and roads were repaired within the week and the bullet train service was resumed within 49 days. Also, four days after the disaster fourteen ports were entirely or partially usable and the affected airport reopened for emergency services. This rapid re-opening of critical transport infrastructure helped to facilitate effective relief activities in the area. (World Bank Institute, 2012).



Steps in infrastructure rehabilitation, Source: World Bank Institute (2012) *Knowledge Notes, Cluster 4: Recovery planning* (page 6)

Highlighted below are a selection of the defining features of Japan's emergency and post-disaster governance structures, financial arrangements, emergency procedures and operations mechanisms which facilitated rapid and efficient recovery after the 2011 earthquake. The seismic design features and early warning systems that limited railway damage are also described in detail. Additionally, some lessons that emerged from the EEFIT field mission to Japan two years later are covered.

### POLICIES, INSTITUTIONS AND PROCESSES

- **Emergency headquarters.** The Ministry of Land, Infrastructure, Transport and Tourism set up its emergency headquarters about 30 minutes after the quake.
- **Pre-disaster agreements with the private sector.** An emergency agreement has been in effect since 2006 in Japan between the GSI, an agency under Japan's Ministry of Land, Infrastructure, Transport and Tourism, and APA, which has a shortlist of 94 member companies best suited for carrying out surveys following a disaster. Shortlisted companies agree to keep resources available for immediate mobilisation. This EA allows GSI and APA to work out details in advance including emergency contact information, necessary technical specifications and shorthand methods for communication, all of which are regularly revised and updated. APA members annually register their interest to join the

shortlist. In the aftermath of a disaster APA will recommend companies at the request of GSI, who then enter into a contract with this recommended company/companies on a fast track sole source contract basis (UNISDR, 2013).

- **Established coordinating bodies to harmonise reconstruction solutions.** The Ishinomaki City Recovery and Community Development Council's role was to coordinate the various project managers and agencies dealing with land use, structural engineering solutions etc. to explore and harmonise recovery options. There is otherwise a tendency for agencies to provide a quick response by remaining within the scope of their authority (EEFIT, 2013).

- **Pre-arranged twinning arrangements between localities.** Twinning arrangements were pre-arranged between localities in disaster-affected areas and their counterparts in unaffected areas to deal with emergencies. Local governments suffered serious damage to their office facilities, computer services were damaged, data lost, and many lost their public officials (221 died or remained missing in 17 municipalities in the three hardest hit prefectures). Other prefectures and municipalities took the initiative to send their own public officials to help – around 79, 000 in capacities ranging from civil engineering, urban planning to social work and finance were dispatched from all over Japan until the end of 2011.

- **'Like for like' reconstruction principles versus 'betterment/resilient' principles.** There have been some issues regarding incorporating new recommendations into newly constructed defences as the disaster law in Japan says it is a principle to replace structures 'like for like', which in controversial cases may not be the most effective solution'. (EEFIT 2013: 58)

#### FINANCIAL ARRANGEMENTS AND INCENTIVES

- **Flexible budget arrangements expedited project implementation.** Within 10 days of the disasters local governments reported their infrastructure damage to the national government and request a national subsidy. The national government conducts a disaster assessment within 2 months of the disaster and approves the subsidy. Even before applying for the subsidy local governments can begin implementing their projects.

The national governments subsidises two-thirds of the project costs, and much of the local government's share is covered by national tax revenues. Thus, local governments actually cover only 1.7 percent of the costs at most. Japan implements a special corporate tax for reconstruction and a special income tax, the government also enforces pay cuts for national public employees and asks local governments to cut salaries. It additionally issues reconstruction bonds and establishes a special account for reconstruction.

- Civil engineering structures are covered by insurance in Japan, up to a maximum payout limit.

#### OPERATIONS AND MAINTENANCE

- **Identified and prioritised the clearing of critical access routes.** The first priority was to open up the 15 eastward access routes, which were cleared within four days. 13 days after the disaster the main expressway was open to general traffic. Operation toothcomb allowed for the quick rehabilitation of roads following the disaster. All the debris was cleared on 16 routes stretching out from various points on the major north-south artery and reaching east to the coastal areas worst hit by the tsunami.

- **Coordinated to address labour shortages in a post disaster situation.** A shortage of labour in October 2011 was jeopardizing projects, the MLIT thus organised the 'Liaison Council for Smooth Execution of Recovery and Reconstruction Projects' with members of the state, Iwate, Miyagi and Fukushima prefectures, Sendai city and Japan Federation of Construction Contractors and National Construction Contractors Association. In 2012 the following steps were taken: (1) labour unit costs for



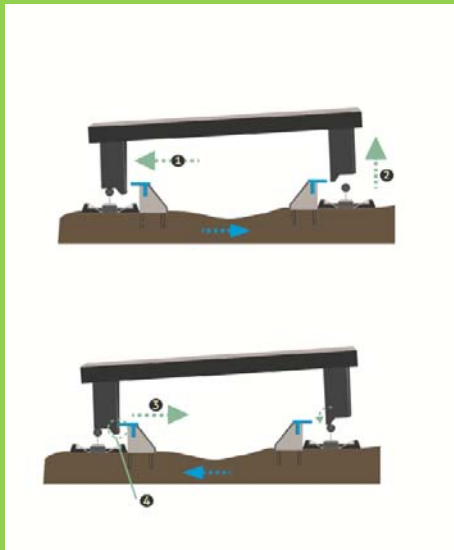
designing public projects were revised to reflect current labour cost levels and (2) lead engineers were allowed to cover multiple projects, as long as they were related and close to each other. (White Paper on Land, Infrastructure, Transport and Tourism in Japan, 2011)

- **Develop land registers.** The development of land registers was a key lesson emerging from the March 11<sup>th</sup> earthquake to clarify boundary disputes in the reconstruction process.

#### TECHNICAL – PLANNING AND DESIGN

Japan's seismometer along with the quakeproof structures and anti-derailing systems undertaken after 1995 and 2004 earthquakes, were critical in avoiding critical damage and accidents.

**Anti-derailing systems for railways** - Technology to prevent derailment and deviation during an earthquake, comprised derailment prevention guards which were installed on the inside of rails in high risk areas, including high speed points, to prevent rocking derailment. Other measures included "deviation prevention stoppers" installed in the centre of Shinkansen (high speed train) rolling stock bogies. The anti-derailing guard rail is directly fixed onto the tie in parallel to the rail to ensure that the wheel on one side always remains on the rail. The guard rail can also easily be turned over to the centre of the track for maintenance work. (Morimura, 2011).



The top figure shows how rocking derailment occurs in an earthquake, and the occurrence of lateral wheel displacement (1) and wheel uplifting (2). The bottom figure shows how anti-derailing guard rails at point (4) prevent derailment. (figure adapted from Morimura, 2011)

#### - **Seismically reinforced railways and surrounding infrastructure**

This included the seismic reinforcement of columns of elevated rail structures, taking into account the latest predicted ground motion data (from the Japanese government).

Following the Great East Japan Earthquake (2011), surveys of railway viaducts and bridges found that this seismic reinforcement undertaken before the earthquake had largely been effective (where subject to seismic loads and not affected by the Tsunami – see JCSE, 2011). This validated the design approach to improve ductility and not strength.

Significant flexural damage to columns was still noted where seismic reinforcement against shear failure had been carried out, but where columns with spiral bars at the column hinge were used (in accordance with new seismic standards) to provide a very high deformation capacity, no extensive

damage was found, aside from flexural cracks. Also columns which had been seismically reinforced with steel casings were undamaged.

Bridge piers and columns without previous seismic reinforcement did suffer damage and it was also found that pre-tensioned pre-cast catenary poles did not perform well, suffering damage and breakage and the subsequent repairs to the electrical system were the biggest obstacles to the resumption of operations.

Whilst seismic reinforcement measures saved railways from the worst damage and not one train passenger died the day of the earthquake, Kimitoshi Sakai, earthquake and structural engineer at the Railway Technical Research Institute wrote in the Railway Technology Avalanche magazine that a common standard of seismic countermeasures should be introduced. Measures introduced after the earthquakes in 1995 and 2004 were conducted independently of each other. With a national system, however, appropriate seismic countermeasures could be chosen according to the area's seismicity, ground conditions, structural conditions and level of traffic. (Fischer, 2011).

#### SOURCES:

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Joint Survey Team of the JSCE Concrete and Structural Engineering Committees (2011) *Report on Damage to (Civil Engineering) Concrete Structures in Fukushima Prefecture (First Report) (on the damage caused by the Great East Japan Earthquake)*. [Online] Available from: [http://www.jsce.or.jp/committee/concrete/e/newsletter/newsletter25/index\\_files/JSCEreport\\_damage\\_inFukushima.pdf](http://www.jsce.or.jp/committee/concrete/e/newsletter/newsletter25/index_files/JSCEreport_damage_inFukushima.pdf) [accessed: 20/05/2014]

## CASE STUDY 19: Review of Port, Harbour and Bridge Design following the Great East Japan Earthquake and Tsunami (2011): Japan

An earthquake magnitude 9.0 Mw; depth 32km; location 150km offshore, representing a probability of 1 in 1,000 year return period hit Japan in 2011. The maximum tsunami inundation height was 9.5m and the range of the vertical displacements (subsidence) varied from -20cm to -84cm.

An evaluation of the performance of Japan's structures under tsunami loads is found in a report by Chock, et al., (2013) Key lessons they identified learnt from this event were that:

- Probabilistic analyses in addition to historical reviews are required to identify acceptable risk based design criteria to estimate the maximum credible or considered tsunami.
- There is also a need to estimate flow depths and velocities in order to estimate the hydrodynamic forces applied to structures during a tsunami. Velocities at the leading edge of swell at this event have been estimated to be 12.3 to 13.4m/s.
- A tsunami accumulates an enormous amount of debris consisting of vegetation, building materials, automobiles, boats, ships and even entire buildings. The resulting debris flow will impact structures in the paths of the tsunami. Timber structures appear to be most susceptible to debris impact damage, but individual members in concrete and steel framed structures can also suffer damage or even failure. The debris damage from floating ships can be significant.

The key points below are extracted from the report by Chock et al., (2013) and provide further detail on the performance of Japan's infrastructure under tsunami load.

### TECHNICAL – PLANNING AND DESIGN

**- When assessing/retrofitting/designing any transport systems with strategic bridges in locations exposed to tsunamis, there is a need to take into account that any exposed areas of a bridge can result in the entire structure being subject to large lateral loads.**

**Most post-tsunami bridge failures relate to connection details of how the structural load path passes between decks, piers, abutments to the foundations.** This is illustrated as follows. Consider where a pier top connection is designed not to fail, and where the assessed theoretical tsunami flow velocity to cause failure of the piers is identified to be 3.9m/s. In contrast, if the pier connection has been designed to fail, and the bridge deck thereby removed as a consequence of a tsunami lateral load impact, then the same piers would withstand flow velocities of up to 11.5 m/s prior to flexural failure. For anticipated tsunami flows, bridge decks must therefore be designed for hydrodynamic lateral loads in addition to both hydrostatic and hydrodynamic uplift.

**All rail bridges should be designed for appropriate seismic impacts,** to avoid any major disruptions. The failure of a single railway bridge can result in failure of an entire rail line serving many communities along a coastline. This is particularly important as there is no easy way to replace a failed railway bridge with a temporary structure, because of grade and alignment requirements, as well as the magnitude of rail traffic loading. (In contrast, alternate routes, temporary by-pass roadways, and temporary steel-truss bridges can be built rapidly where a road has been destroyed after an event, providing access to cut-off communities.)

**Ports and harbour design should be designed for 'Safe Failure'** to prevent total loss of sections of piers, wharf walls, and their tiebacks. For example, while pile-supported wharves (quays) are seldom damaged, non-pile supported wharves can be subject to settlement of backfill due to seismic consolidation of loose soils or liquefaction with lateral spreading. Bulkhead walls (quay walls) can be subject to lateral failure due to soil erosion or loss of restraint stiffness due to scour at tieback anchorages. Also, scour and lifting or undermining of even very thick slab wharf pavements can occur.

**Design Sea Walls for 'Safe Failure'** (see separate case study) by ensuring they can overtop without failure. Seawalls which do not overtop tend to perform without failure in areas with lesser tsunami heights, but where overtopping occurs, damage can be extensive, generating massive debris which can travel with inflow. Low seawalls remaining intact with adequate foundation systems can still be effective in slowing flow velocities/momentum. Similarly, Tetra-pod armour units or similar may be moved but normally survive and maintain function during a disaster event. In contrast, concrete lined compacted earth barriers are generally not effective and failure mechanisms numerous.

**SOURCE:**

Chock, G., Robertson I., Kriebel, D., Francis, M., and Nistor, L. (2013) *Tohoku, Japan, Earthquake and Tsunami of 2011: Performance of Structures under Tsunami Loads*. American Society of Civil Engineers. Available from:  
<http://www.asce.org/Product.aspx?ID=2147487569&ProductID=187776013> [accessed: 20/05/2014]

## CASE STUDY 20: Oregon's Resilience Plan for Infrastructure – Prioritising and Categorising Lifeline Routes

The Oregon legislature, noting the likely devastating impact of a Cascadia earthquake, passed a House Resolution charging the Oregon Seismic Safety Policy Advisory Commission to develop a resilience plan. The Oregon Resilience Plan defined the resilience goal of a transportation network to first facilitate immediate emergency response, and second restore general mobility within specified time periods.

In order to establish resilience goals the task group first assessed the transportation network in four geographical areas, and then established resilience targets for all transportation facilities. It prioritised highways in three tiers: Tier 1 –small backbone system allowing access to vulnerable regions, major population centres and areas vital for rescue and recovery; Tier 2 – larger network that provides access to most urban areas and restores major commercial operations; and tier 3 – a more complete transportation network. Resilience targets were then established at three levels:

- Minimal: minimal service is restored primarily for emergency responders, repair crews, food and critical supplies
- Functional – sufficient to get the economy moving but there may be fewer lanes in use, some weight restrictions and lower speed limits
- Operational – restoration is up to 90% of capacity and it is sufficient to allow people to commute to school and to work.

An extract from Oregon's resilience assessment is found below, highlighting the desired performance targets and current recovery conditions. On the basis of this assessment the Task Force recommended a multi modal plan that strengthened particularly critical components of the transportation system – highways, air, rail, ports and local access roads – in phased steps so that mobility could be increased in the most cost effective way.



## Oregon Transportation Resiliency Status

**\*Key to the Table**

TARGETS TO ACHIEVE DIFFERENT LEVELS OF RECOVERY:										
Minimal: (A minimum level of service is restored, primarily for the use of emergency responders, repair crews, and vehicles transporting food and other critical supplies.)	R									
Functional: (Although service is not yet restored to full capacity, it is sufficient to get the economy moving again— e.g. some truck/freight traffic can be accommodated. There may be fewer lanes in use, some weight restrictions, and lower speed limits.)	Y									
Operational: (Restoration is up to 90% of capacity: A full level of service has been restored and is sufficient to allow people to commute to school and to work.)	G									
ESTIMATED TIME FOR RECOVERY TO 60% OPERATIONAL GIVEN CURRENT CONDITIONS:	S									
ESTIMATED TIME FOR RECOVERY TO 90% OPERATIONAL GIVEN CURRENT CONDITIONS:	X									
Comparison of Target States and Estimated Time for Recovery										
Infrastructure Facilities	Event Occurs	0-24 hours	1-3 days	3-7 days	1-4 weeks	1-3 months	3-6 months	6-12 months	1-3 years	3+ years
<b>Central Oregon Zone</b>										
<b>► OREGON STATE HIGHWAY SYSTEM</b>										
<i>State Highway System - Tier 1 SLR <sup>1)</sup></i>										
Roadways			R	Y	G			S	X	
Bridges			R	Y	G/S		X			
Landslides			R	Y	G			S	X	
<i>State Highway System - Tier 2 SLR</i>										
Roadways			R		Y	G			S	X
Bridges			R		Y	G/S		X		
Landslides			R		Y	G		S	X	
<i>State Highway System - Tier 3 SLR</i>										
Roadways				R		Y	G		S	X
Bridges				R		Y	G/S		X	
Landslides				R		Y	G		S	X
<i>State Highway System - Other Routes</i>										
Roadways					R		Y	G	S	X
Bridges					R		Y	G	S	X
Landslides					R		Y	G	S	X
<b>► AIRPORTS &amp; AIR TRANSPORTATION</b>										
<i>Tier I - Oregon Airports System</i>										
Redmond Municipal Roberts Field Airport - FEMA		R	S		Y	G	X			
Klamath Falls Airport		R	S		Y	G	X			
FAA Facility			R	Y	G					
<b>► OREGON RAIL TRANSPORTATION</b>										
<i>UPRR</i>										
CA/OR State Line to Bieber Line Jct. (Klamath Falls)			Y	G	S	X				

**SOURCE:**

Oregon Seismic Safety Policy Advisory Commission (OSSPAC) (2013) *The Oregon Resilience Plan: Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami - Report to the 77<sup>th</sup> Legislative Assembly*. OSSPAC . Salem, Oregon (02/2013)

Available from: [http://www.oregon.gov/OMD/OEM/ossnac/docs/Oregon\\_Resilience\\_Plan\\_Final.pdf](http://www.oregon.gov/OMD/OEM/ossnac/docs/Oregon_Resilience_Plan_Final.pdf) [accessed: 20/05/2014]

## CASE STUDY 21: Great East Japan Earthquake and Aviation – Disasters and the Private Sector

When the Great East Japan Earthquake struck in 2011 there was enormous demand for flights as all land transport links were cut off over an extensive area and the delivery of emergency relief as well as the transportation of medical and relief teams and evacuees were being seriously impeded. A UNISDR (2013) report on Private Sector Strengths Applied: Good Practices in Disaster Risk Reduction in Japan included a case study on Japan Airlines Co. Ltd.'s efficient response to the earthquake. The key points from this report are summarised below.

### OPERATIONS AND MAINTENANCE

- **Relaxed regulatory controls.** The aviation authorities temporarily relaxed regulatory controls and Japan Airlines Co., Ltd (JAL Group) cancelled and adjusted the aircraft size of regular flights to free up large aircraft for the Tohoku region that was hit, which involved re-coordinating plane assignments on a daily basis.
- **Established procedures to mobilise and reallocate personnel to disaster zones.** Additionally, cabin attendants, ground staff, airport equipment and machinery were sent to airports all over Tohoku to handle the extra flights. In the first 20 days JAL flew an extra 561 flights to the disaster affected areas, with a seat occupancy rate of 84.4%.
- **Created a disaster contingency manual and put emergency procedures in place.** The JAL immediately activated the procedures in its regularly revised Disaster Contingency Manual and set up a disaster response headquarters with the CEO at its head. Within ten minutes of the earthquake JAL's operations control centre (OCC) cancelled flights bound for Sendai and Haneda where reports were coming in that a tsunami was imminent, instructed Sendai Airport to direct passengers and staff to safer areas in the airport and divert circling aircraft to other airports in the area. Departments in charge of flight route scheduling and equipment management were amalgamated so decisions could be based on demand assessments and put in place quickly.
- **Introduced redundancy into the emergency operating system.** After the disaster JAL established a procedure in case Tokyo suffered a major earthquake as the OCC which controls all flights is located in Tokyo. In this case JAL's Osaka Airport branch would be temporarily responsible until another OCC was established.
- **Improved the reliability of emergency communication.** A key lesson from the disaster was the need to establish a reliable means of communication - In coordinating new flight schedules it is necessary to obtain information quickly, and while most communications were down public telephones with emergency batteries and telephones with backup power sources were still operational.
- **Strong organisational ethos and staff identity.** One of JAL's corporate philosophies is 'each of us makes JAL what it is'. This encouraged decisive actions and decision making in the field.

### SOURCE:

UNISDR (2013) *Private Sector Strengths Applied: Good practices in disaster risk reduction from Japan*. Available from: [http://www.unisdr.org/files/33594\\_privatesectorstrengthsapplied2013di.pdf](http://www.unisdr.org/files/33594_privatesectorstrengthsapplied2013di.pdf) [accessed: 20/05/2014]

## CASE STUDY 22: Temporary Stabilisation and Future Redundancy Need Identified following Wave Damage to Coastal Rail Infrastructure (2014): Dawlish, United Kingdom

In the UK in 2014 severe winter storms damaged the Great Western Main Line (originally built in 1846), the main rail link to the west of the country. The total resulting damage was variable across a 525m length but included 80m of ground, including track bed and supporting seawall being washed away, leaving tracks suspended in mid-air. Damage was also caused to the parapet wall, which was critical in protecting the track ballast. There were no injuries, as no trains were running during the events.



Source: Smalljim, This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported licence. Date 7 February 2014.



Source: Geof Sheppard, This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported licence. Date 12 April 2014.

Priority was given to the emergency response phase after both storms, due to the high importance of keeping with vital rail link open. The overall target for resumption of rail services was within six weeks of the initial damage. The following key elements enabled this to take place:

### OPERATIONS AND MAINTENANCE

- **Effective Early Warning System:** the initial storm was forecasted and the rail line was closed to trains and staff relocated to safe distances. The rail operator had good weather forecasting systems in place and trains were stopped from running and rail staff were relocated and no human losses occurred.

- **A comprehensive damage inspection was carried out identifying secondary dangers (unstable slopes away from the main damage area) and to identify the critical path for reconstruction works:** Following the storm, the damage was assessed with defects given a red, amber, green classification, depending on their importance for getting the railway open again. The priority action was to protect the existing ground and assets from further damage. This was achieved by removing the damaged track and protecting the communication cables running adjacent to the track, including rail signalling and the Global Crossing Cable connection to the USA. Work also progressed on building a cable bridge so that services and signalling equipment could pass over the rail bed to allow reconnection of cabling.

This inspection also identified that 20,000 tonnes of cliff face near Teignmouth has sheared away above the railway. As a result the slope above the track needed to be stabilised before the track could safely reopen. The sheared cliff face was removed using 'Spidermax', a specialised piece of kit that allows mechanical work to reprofile the top of the cliff edge. An additional technique was to use a high-pressure water cannon to dislodge fallen earth.

- **Emergency Works to Prevent Further Damage: Innovative use of shipping containers as a temporary sea defence to quickly preventing damage from a secondary storm.** The final part of the

emergency works was to further protect the damaged area from wave action with the use of 11 ten-tonne shipping containers welded together, forming a temporary breakwater. These were filled with sand and stone and placed in front of the damaged area. At low tides, sprayed concrete was also used to protect the exposed scar from further damage. **Evidence of success:** Before the main concrete pour took place another storm hit the affected area, and caused further damage, but the temporary breakwater proved effective despite sustaining damage. Following the second storm, additional shipping containers were put in place to protect the new damage to the seawall.

#### TECHNICAL – PLANNING AND DESIGN

**Post Disaster Reconstruction Works: Site specific standard construction solution – was enabled by the temporary sea defence.** Following the temporary repair, 5,000m<sup>3</sup> of insitu concrete was used to reinstate the void. Walls were tied into the foundations with drilled and grouted steel bars. A reinforced concrete strip footing was poured on the rear of the mass concrete formation. Two sets of pre-cast vehicle barriers ('L-shaped' units) were used. This enabled the rear row acted as a retaining wall and the front row acting as a permanent shutter for the track bed channel and to contain the track ballast.

**Long Term Strategic Planning for Redundancy.** Prior to this failure, over £10 million had been invested in sea defences in this area, but the level of damage was still unprecedented. With rising sea levels and increased frequency of storm events increasing with climate change the rail operator is now reconsidering alternative options to re-route trains inland in the longer term. This would also reduce redundancy into the transport network so the strategic link from the capital, London to the South-West of England is maintained in the case of future incident, or maintenance works.

#### SOURCES:

Pitcher, G. (20/02/2014) Dawlish rail washout triggers call for inland lines. In: *New Civil Engineer*, 20 February 2014, p.5. EMAP.

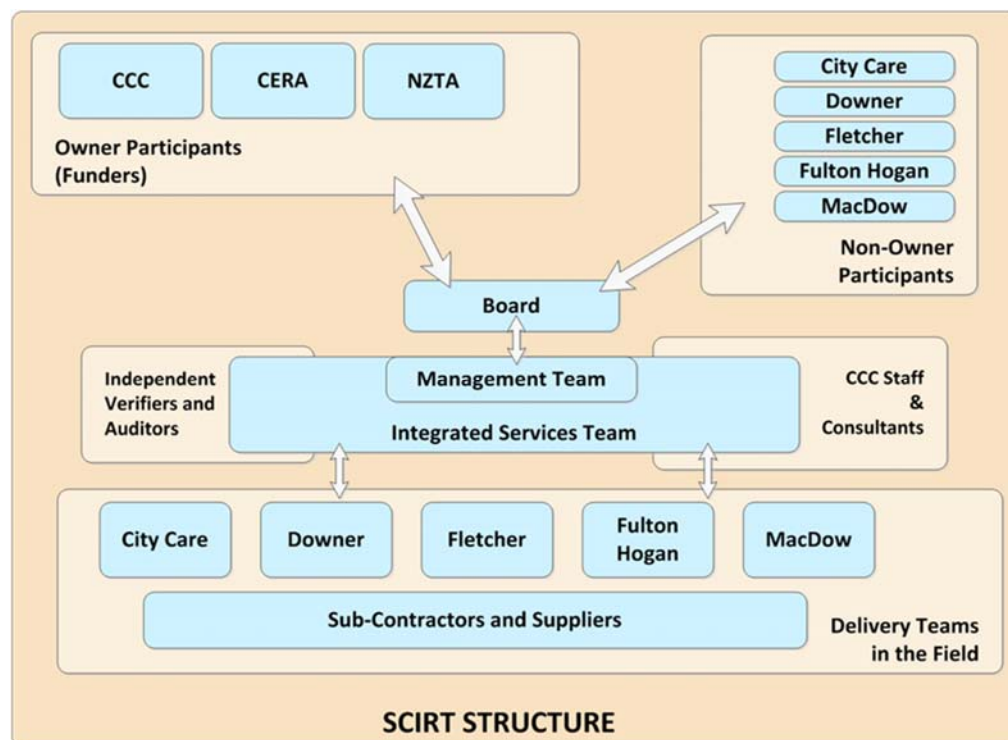
Masters, J. (05/03/2014) Concrete storm repairs: plugging the storm breach in Dawlish. In: *New Civil Engineer*, 05/03/2014, p.18. EMAP.

<https://www.networkrail.co.uk/timetables-and-travel/storm-damage/dawlish/>

## CASE STUDY 23: Post Disaster Institutional and Operational Arrangements Following Christchurch Earthquake (2011): South Island, New Zealand

In September 2011, following two major earthquakes in Christchurch on 4<sup>th</sup> September 2010 and 22<sup>nd</sup> February 2011, the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) was established and tasked with repairing and reconstructing the horizontal infrastructure - pipes, wastewater, storm water, roads, walls and road structures. SCIRT is a mixed team of public and private organisations that have agreed to participate in an alliance contract. The SCIRT alliance involves three owner participants (the three public entities) – Christchurch City Council (funder and asset owner), New Zealand Transport Authority (funder and asset owner), and Canterbury Earthquake Recovery Authority (funder only). It has three functional layers – a governance framework, an integrated services team (which has asset assessment and design functions) and five delivery teams (see diagram below).

A selection of defining aspects of the governance and operation of SCIRT are outlined below, providing points of learning for future recovery models. Further detail regarding challenges in the specific context of SCIRT’s governance and operation be found in the New Zealand’s Office of the Auditor General report: *Effectiveness and efficiency of arrangements to repair pipes and roads in Christchurch* (2013) and MacCaskill (2014).



Source: Rod Cameron, SCIRT



## **POLICIES, INSTITUTIONS AND PROCESSES**

- **Flexibility and collaboration – managing uncertainty.** The key aspect of the alliance arrangement is the emphasis on collaborative approach between the owner and non-owner participants. Given the scale of damage following the second major earthquake in February, there was a realization that the more traditional contracting arrangement set up after the September earthquake was no longer appropriate for the reconstruction of horizontal infrastructure. The alliance contract is based on a shared pain-gain financial arrangement amongst the stakeholders. It is suited to the post-disaster context where the exact scope of works is uncertain and condition of underground assets needs to be clarified as work progressed, with on-going risk of further earthquakes and with the significant demand for design and construction resources.

- **Clear roles and responsibilities.** The 2013 Audit report criticized CERA for not providing effective leadership and strategic direction to SCIRT. It highlighted that roles and responsibilities are sometimes blurred. This can create ambiguity over how decisions are made and who makes these decisions. An aspect particular to the SCIRT approach is that there are three owner participant organizations that bring different views to the table. However, involvement of multiple organizations in the reconstruction of infrastructure is not unusual in a recovery situation.

- **Delayed land use decisions may impact progress of infrastructure repair.** The 2013 Audit report pointed out that SCIRT's rapid pace of operation was misaligned with the slower progression of strategic planning for the wider rebuild. For example, there is a significant area of residential re-zoned land in Christchurch, which is deemed to be at high risk of future earthquake-related damage (such as liquefaction and rockfall) and is considered uneconomical to repair on an individual property basis. CERA is responsible for deciding the future use of this land. There is currently no decision regarding this future use. This, and the associated uncertainty around flood defence options (which are under consideration with the Council), could delay repair works under SCIRT's remit.

- **Defining scope of repair works requires negotiation and trade-offs.** The SCIRT Alliance Agreement defines the desired level of repair for horizontal infrastructure as "a standard and level of service comparable with that which existed immediately prior to the September 2010 earthquake". However, it was difficult to define the pre-earthquake levels of service in a way that helps to inform asset rebuild or repair decisions. There has also been an effort to introduce improvements, such as increasing pipe capacity. Introducing improvements raises the level of service, but also raises the cost and requires extra funding.

The starting point for the reconstruction was "like for like" replacement of damaged infrastructure. However, this is not necessarily a straightforward decision. Design using modern materials and standards inherently introduce resilience to a network that was badly damaged. However, there is a funding constraint, which means that engineers have to carefully consider how to best spend the available funds across the different assets, and across the city, in a way that leaves a manageable legacy for the Council. Decisions tend to be more difficult in areas of low to moderate damage, where there is potentially some operational life left in the asset, compared to highly damaged areas that clearly need rebuilding as opposed to patch-repair.\*

A key document for guiding replacement and repair decisions is the Infrastructure Recovery Technical Standards and Guidelines, which was developed after the earthquakes. This document provides the basic framework for a consistent approach for determining appropriate treatment options. This document has evolved throughout the recovery effort. There has also been a mechanism in place to challenge this guidance, or to apply for extra funding where opportunities for improvement have been identified. The design engineer creates a case and a "Scope and Standards Committee", with representatives from each of the owner participant organizations, are the final arbiter on these decisions (discussed further in MacAskill, K., (2014)



It took some time to negotiate funding arrangements between the client organisations. An official cost sharing agreement was signed in June 2013. However, there is ongoing demand for funding from many aspects of post-disaster recovery, requiring funder attention to a prioritisation process to balance the various demands and agree on the funding to be applied to the horizontal infrastructure.

#### **SOURCES:**

New Zealand's Controller and Auditor General (2013) *Audit Report*. [Online]  
Available from: <http://www.oag.govt.nz/2013/scirt> [accessed: 20/05/2014]

Christchurch City Council (2011) *Christchurch Infrastructure Rebuild Plan: How we plan to fix our earthquake damaged roads and underground services*. Christchurch, New Zealand.  
Available from: [http://resources.ccc.govt.nz/files/canterburyearthquake/scirt-infrastructure-rebuild-plan\\_web.pdf](http://resources.ccc.govt.nz/files/canterburyearthquake/scirt-infrastructure-rebuild-plan_web.pdf) [accessed: 20/05/2014]

MacAskill, K. A. (2014) Postdisaster Reconstruction of Horizontal Infrastructure Systems: A Review of the Christchurch Rebuild. In: Randy R. Rapp & William Harland (Eds.), *The Proceedings of the 10th International Conference of the International Institute for Infrastructure Resilience and Reconstruction (I3R2) 20-22 May 2014*. (pp. 189-195). West Lafayette, Indiana: Purdue University.  
Available from: <http://docs.lib.purdue.edu/i3r2/2014/rrr/8/> [accessed: 20/05/2014]

Information was also kindly provided by Rod Cameron (Value Manager at SCIRT) and Kristen MacAskill (PhD student examining decision making in post-disaster urban infrastructure reconstruction activities at the Centre for Sustainable Development, Cambridge University)

## CASE STUDY 23: Sandy Task Force and Rebuilding Resilient Infrastructure

The Hurricane Sandy Rebuilding Task Force was established on December 7th 2016 charged with coordinating federal interagency efforts. It was chaired by the Secretary of Housing and Urban Development (HUD) and including members from 27 different federal executive branch agencies (including transportation) and White House offices. The Task Force was supported by an advisory group composed of many state, tribal and local elected leaders from the most severely impacted cities and towns. The Task Force's functions were to coordinate rebuilding efforts, 'identify and work to remove obstacles to resilient rebuilding in a manner that addresses existing and future risks and vulnerabilities and promotes the long-term sustainability of communities and ecosystems' (Executive Order 13632 in Hurricane Rebuilding Strategy: 167)

The Task Force's primary task was to issue the Hurricane Sandy Rebuilding Strategy which lists 69 guidelines for the recovery, many of which were already adopted by the time it was published. As required, the Task Force terminated 60 days after the publication of this strategy and the Federal Emergency Management Agency assumed the majority of the coordinating role, working with HUD and other lead agencies for the Recovery Support Functions established by National Disaster Recovery Framework.

A selection of some of the guidelines from the Task Force's report (2013) 'Hurricane Sandy Rebuilding Strategy: Stronger Communities, A Resilient Region' are summarised below.

### POLICIES, INSTITUTIONS AND PROCESSES

#### Data sharing and accountability – the role of the Project Management Office

The Task Force created PMO in January 2013 to serve as a data-driven cross-agency and help speed assistance to and maximise the efficient use of funds in the recovery process. The PMO worked closely with agencies, OMB, and the oversight community, such as the agency Inspectors general and the Recovery Accountability and Transparency Boards (RATB). It was also established to leverage the lessons learnt from Hurricane Katrina and the best practices from ARRA. \$50 billion in relief funding was provided and administered through more than 60 different programs. The PMO served as the central source of information about the progress and performance of this funding. Its role was to: (1) promote the transparent use of funds by developing financial and performance updates that were accessible to the public; (2) coordinate matters related to budget execution and performance management across the 19 federal agencies funded by the Sandy Supplemental; (3) collect and analyse agency financial and performance data to understanding the progress of recovery; and (4) provide oversight support to RATB and Agency Inspectors General by providing data and information and bringing together agency stakeholders. The need for accountability and transparency emerged as a key lesson from Hurricane Katrina.(HUD, 2013: 153 – 15)

### FINANCIAL ARRANGEMENTS AND INCENTIVES

- **Transportation funding should be aligned with national policy goals** - Federal funding has included an interim final rule in its emergency relief program that the Federal Flood Risk Reduction Standard (best available flood hazard data plus one foot of freeboard) applies to the rebuilding of structures.

The report also noted that new resilience grants will be based on the Transportation Investment Generating Economic Recovery (TIGER) program and incorporate the Infrastructure Resilience Guidelines and other resilience components to develop a specific program for the Sandy affected region. The goal will be to ensure public transit systems can perform their critical functions in the face of future disasters and impacts of climate change. (HUD, 2013: 71-72)

NOAA is also promoting the use of green infrastructure by providing financial support, information and tools and services for coastal communities. **Coastal Resilient Networks grants** will also support an economic assessment to analyse the different levels of inundation protection and benefits of shoreline rebuilding and restoration alternatives in the region (HUD, 2013: 73).

#### OPERATIONS AND MAINTENANCE

##### - Develop clear infrastructure resilience guidelines.

Infrastructure Resilience Guidelines: Following the Sandy recovery Effort the Task Force created an interagency working group that developed a shared set of Federal resilience guidelines to govern infrastructure investment. These 7 guidelines are:

**1) Adopt a science based, forward looking comprehensive analysis that in the project design and selection includes an assessment of the following criteria:** Public health and safety; direct and indirect economic impacts (financial and opportunity cost of losing infrastructure functions and services after a disaster); social impacts, environmental impacts; cascading impacts and interdependencies across communities and infrastructure sectors; changes to climate and development patterns that could affect the project or communities; inherent risk and uncertainty; and monetisation of the impacts of alternative investment strategies.

**2) Select projects using transparent and inclusive decision processes:** Apply a multi-criteria decision analysis – including a cost-benefit analysis – into funding selection and administration processes and share the decision criteria, evaluation process and findings with all stakeholders.

**3) Work with partners across all levels of governance,** as well as the private sector to promote regional and cross jurisdictional resilience that identifies interdependencies, shares goals and information.

**4) Monitor and evaluate the efficacy and fiscal sustainability of the program,** taking into account changing environmental conditions, development patterns and funding sources.

**5) Promote environmentally sustainable and innovative solutions**

**6) Implement meaningful financial incentives and/or funding requirements to promote the incorporation of resilience and risk mitigation into infrastructure projects**

**7) Adhere to resilient performance standards**

The report recommended that these Infrastructure Resilience Guidelines be adopted nationally (HUD, 2013: 49-53)

#### SOURCE:

US Department of Housing and Urban Development (HUD), Hurricane Sandy Rebuilding Task Force (2013) *Hurricane Sandy Rebuilding Strategy: Stronger Communities, A Resilient Region*. [Online] Available from: <http://portal.hud.gov/hudportal/documents/huddoc?id=hsrebuildingstrategy.pdf> [accessed: 07/04/2014]

### CASE STUDY 25: Wildfire: 2009 'Black Saturday', Wildfire, Australia

Saturday 7 February 2009. Known as 'Black Saturday', numerous bushfires raged across the state of Victoria, killing 173 people, injuring 414 and affecting tens of thousands. It was one of Australia's worst natural disasters. This case study focusses on the recommendations made by a royal commission (2009 Victorian Bushfires Royal Commission Final Report) which in part covered transport infrastructure. The fires resulted from a culmination of extremely hot and dry weather and high wind speeds. Continuing fires, inaccessible roads and loss of power and telecommunications hindered relief efforts and interfered with communication and mobility. More than \$1 million worth of damage was caused to rail infrastructure. A platform was destroyed as well as 4,200 sleepers and two rail bridges. Following repair works lines were fully operational nine days later. The fires also meant roads were closed for safety reasons.

#### POLICIES, INSTITUTIONS AND PROCESSES

Prior to the disaster the authorities were familiar with dealing with bushfires and tools and guidance where available to assess and manage the risk, but however there appeared to be a lack of a systematic approach and VicRoads were mandated by the Royal Commission to carry out detailed risk assessments for every road they were responsible for (see **TECHNICAL – PLANNING AND DESIGN box**). VicRoads consequently developed detailed these risk assessments based upon main objectives of roadside fire management, which they identified as:

1. Prevent Fires on Roadsides
2. Contain Roadside Fires
3. Manage Safety of Users
4. Provide Control Lines (roads which can help provide a 'fire break' and provide good access for fire suppression)
5. Recovery from Roadside Fires

#### TECHNICAL – PLANNING AND DESIGN

To meet the objectives outlined in the **POLICIES, INSTITUTIONS AND PROCESSES** section Vic Roads carried out the following:

For Objectives 1 and 2 a likelihood /consequence assessment was carried out to determine fire risk for each road). The resulting VicRoads Bushfire Risk Maps (low, moderate, and high risk roads) are uploaded as GIS map, and provide a tool for maintenance of road verges and a planning tool for fire management including treatments. Important likelihood factors include road category, history of ignitions and ability for fire to spread. Important consequence factors include human, economic, environment and cultural assets.

Objective 3 required an assessment of access/egress criteria and potential mitigation measures including vegetation management. It was recognised that it was not possible to ensure safe travel on roads during and after a bushfire, especially during the passage of the fire front.

Risk maps of the road network, both arterial and municipal, are available and should be used in conjunction with the guideline. These maps can be found on the [CFA DropBox](#) and an extract can be seen below. The map goes through several validation processes including field inspections to ground truth it.

#### Railway

In order to cost savings and more consistent safe working practices, V/Line reports that they are pushing towards the use of concrete rail sleepers. Whilst they are more expensive, they last longer and need less maintenance.

<http://www.vline.com.au/pdf/publications/annualreports/annualreport08-09.pdf>

#### **OPERATIONS AND MAINTENANCE**

The Commission reported that five of the 15 fires were associated with the failure of electricity asset. VicRoads was identified as a key stakeholder in identifying and mitigating the risks posted by trees on roadsides that could come into contact with electric power lines. See the Draft *VicRoads Vegetation Management Plan for Electric Line Clearance* (2012) for the management of trees around power lines.

#### **Early Warning Systems**

Following the Black Saturday event, the government with the support of major telecommunication companies, set up a SMS service in Victoria State to provide warnings of extreme fire danger. Whilst the system had initial limitations, further development work was promised by the government.

<http://www.theage.com.au/national/victorians-receive-fire-text-warning-20090302-8mfq.html>

#### **Other early detection systems**

It is useful to consider what approaches countries, other than Australia, have taken in terms of Early Warning Systems (EWS). However, none are identified as relating specifically to transport.

**Indonesia** has an Early Warning System for Forest Fire Management in East Kalimantan, Indonesia based on a National Fire Danger Rating Index and, weather forecast, haze conditions, and hot spots.

The **Mexico Fire Information System (Sistema de Información de Incendios Forestales)** web site offers daily maps of fire weather and fire behavior potential. **The European Union-funded program, Sensor and Computing Infrastructure for Environmental Risks (SCIER)**, uses ground based sensors such as video cameras and hydro-met instruments. The system models predicted effects of wildfires and generates detailed maps to manage the emergency

<http://www.scier.eu/Default.asp?Static=9>.

**Early Recognition System in Germany, Estonia, Mexico, Portugal, and Czech Republic.** Tower-based, automatic forest fire early recognition systems use optical scanning systems with automatic recognition of clouds by day and night.

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## CASE STUDY 26 : Flashflood and Mudflows – Algeria, Boscastle UK, and Solomon Islands.

A flash flood is a surge of water usually along a river bed or dry gulley or urban street potentially causing significant damage, erosion and loss of life. Conducive conditions for flash floods are mountainous areas, hilly and steep slopes which act as a highly responsive watershed, and impermeable or saturated ground.

The hazard can

- develop over very shorter time periods (minutes or hours)
- often less warning and predictability. They can occur within minutes or a few hours of flood if no rain has fallen at the point where the flooding occurs.
- erode loose materials, soil and turn into a mudflow.

Other causes of landslides include landslide dam outbursts (where landslides block a river and create a natural dam which is breached suddenly. Reducing landslides is covered under separate studies but some points are reiterated in this case study), glacial lake outburst flows (GLOF), sudden bursting of river banks and failure of 'engineered' water retaining structures.

### Case studies

#### **Bab El Oued, Algiers, 2001**

Severe urban flash flooding in 2001 resulted in the deaths of 972 victims in less than one hour with severe effects on infrastructure. The flood was exacerbated by the inability of the affected areas to retain floodwaters and roads acting as conduits for the floodwater. This lack of retention was caused primarily by the over development of housing and roadways in the natural valleys present in the hilly terrain in many parts of Algiers, called oueds. These oueds, while the choice of settlement for many, are extremely susceptible to flash floods.

#### **Boscastle, United Kingdom, August 2004,**

Severe flash flooding occurred at this coastal village when intense summer rain over nearby moors, turned a small steep river through Boscastle Village into a destructive torrent. Vehicles and debris became lodged under the bridge and caused water to back up in the village making the flooding worse. The flash floods affected hundreds of homes and businesses and, swept away about 115 vehicles and badly damaged roads, bridges, sewers and other infrastructure. Due to a helicopter aided rescue there were no fatalities

#### **Honiara, capital of Solomon Islands, April 2014**

Heavy rain from a tropical depression, which later became Tropical Cyclone Ita, caused severe flooding in the Solomon Islands at the beginning of April 2014, killing 22 people and affecting over 50,000. The worst affected area was the capital Honiara after the Mataniko River burst its banks on 3 Apr and caused flash flooding. There was extensive damage to bridges (piers, abutments, approaches, scour protection), and service connections were all damaged. Headwalls and wing walls of culverts were damaged and several culverts were completely washed away. The event took place during the day, which is considered to have significantly reduced the loss of life



## TECHNICAL – PLANNING AND DESIGN

### Boscastle

More than £10 million of improvements were carried out. Computer models, video footage and flood simulations were used in the designs. Works included

- River widening and deepening installing a flood culvert to improve flow and replacing a bridge to increase flow capacity;
- The main car park was raised and set back from the river to make space for water and sediment ;
- Installing a flood relief culvert via a new dissipation chamber.

At the time of the floods the operational forecast model had a resolution of 12 km, which was too large to predict this event. Now the forecast model operates with a 1.5 km resolution which is more likely to pick out small scale extreme weather. UK weather warnings are now also issued around the likelihood of severe weather happening and the impact it might have.

### Honiara, capital of Solomon Islands

The planning for the restoration to pre-flood conditions recommended that studies of upstream river catchment activities were carried out which would the inform the hydraulic design, alternative pavement designs and resilient structures designs to accommodate climate change adaptation, and disaster risk reduction have been stolen – partly an operations and maintenance issues).

### Case studies Summary

Structural measures –

- Bio-engineering incorporating biological and ecological concepts to reduce or control erosion, protect soil, and stabilize slopes using vegetation or a combination of vegetation and engineering and construction materials. Consider bamboo fencing, brush layering, Fiberschine (coconut fibre), netting (for example 'Jube netting'), live fascines (bundles of live branches which grow roots and strengthen earthen structures, palisades, wattle fence. All low cost and easy to install, but may need additional works to prevent significant flash flood.
- Catchment works to: increase retention, increase permeability, change land use – terracing, diversion ridges or channels to intercept run-off on slopes, grassed waterways
- River training (banks protection for example using spurs, riprap, ) 'hard engineering', crib walls, check dams, sills to reduce bed erosion, gabions, screen dams, channel lining,
- Other flood control measures – water retention basins, river corridor enhancement, rehabilitation, retaining walls, drop structures (sills, weirs, chute spillways, drop pipes and check & Sabo dams).

Bridge protection: Much damage was done by the debris carried along in the floodwater.

Recommendations post-disaster identified that the resilience of bridges would be enhanced by building back structures with higher decks and larger spans, with fewer piers presenting an obstacle to flow. Piers could be protected by deflectors (though some deflectors used in the past

#### **OPERATIONS AND MAINTENANCE**

##### **Boscastle**

- A 'tree management regime' was introduced to reduce the risk of tree blockage from fallen trees or trees liable to be washed away along the flooding route.
- A 'stone catcher' was installed to reduce the chances of the new highway culverts blocking; and

##### **Honiara, capital of Solomon Islands**

A maintenance regime was recommended to ensure the creeks and drainage infrastructure was kept in good condition and not to impede flows which was a partial factor in the severity of the flooding in places.

#### **SOURCE:**

Algiers

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Solomon Islands

<http://www.adb.org/th/node/42403>

OCHA, 12 May 2014

<https://www.gfdr.org/sites/gfdr/files/Solomon%20RAI%20Flood%20.pdf>

Boscastle

<https://www.gov.uk/government/news/tenth-anniversary-of-boscastle-and-north-cornwall-floods>

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<http://www.metoffice.gov.uk/news/in-depth/Boscastle-10-years>

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