#7183546 Overview of Engineering Options for Increasing Infrastructure Resilience

FINAL REPORT

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WORLD BANK GROUP

About the Project

The Overview of Engineering Options for Increasing Infrastructure Resilience Project, Contract #7189546, is funded by the World Bank Group with the Global Facility for Disaster Reduction and Recovery. The objective of this project is to prepare a flagship report about infrastructure resilience that investigates the impacts of natural disasters from the loss of (lifeline) infrastructure services and from supply-chain effects. This project also aims to support the development of public policies and interventions that make economic systems more resilient.

About the World Bank Group

The World Bank Group is one of the world's largest sources of funding and knowledge for developing countries. Its five institutions share a commitment to reducing poverty, increasing shared prosperity, and promoting sustainable development. The World Bank Group is committed to open development and has opened its data, knowledge, and research to foster innovation and increase transparency in development.

About the Global Facility for Disaster Reduction and Recovery

The Global Facility for Disaster Reduction and Recovery (GFDRR) is a global partnership that helps developing countries better understand and reduce their vulnerability to natural hazards and climate change. Launched in 2006, GFDRR provides technical and financial assistance to help disaster-prone countries decrease their vulnerability and adapt to climate change.

Miyamoto International

Miyamoto International is a global earthquake + structural engineering, project management, and construction management company that provides critical services that sustain industries and safeguard communities around the world. Miyamoto specializes in Disaster Resiliency Engineering along with disaster risk mitigation, response, and reconstruction.

Disclaimer

The opinions, findings, and conclusions stated herein are those of the authors and do not necessarily reflect the views of the World Bank Group or GFDRR.

Acknowledgment

The data and work presented in this document are based on technical research and data presented by a number of authors. When available, these contributions are listed as part of the references. The pictures, photographs, and other graphical information that are used in this report are based on the contributions of many organizations and individuals and were obtained from the internet.

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EXECUTIVE SUMMARY

According to the World Economic Forum's most recent *Global Risks Report* (2019), extreme weather events and natural disasters in 2018 were ranked in the top five global risks, in terms of both likelihood (first and third, respectively) and impact (second and fifth, respectively). The same report ranks these two events first and second in terms of likelihood to occur. Accordingly, natural disasters have a high likelihood of occurrence and have a high impact.

In risk mitigation, typically, a risk impact matrix is developed, based on the probability of a risk occurring and the impact of the risk. Table 1 shows an example. Risks with a high likelihood and a high impact are the most critical and require the most attention. The likelihood of natural disasters varies, depending on the natural environment (e.g., location and disaster type); therefore, consequences cannot be accurately predicted. However, because their impacts are usually high, it is important to evaluate and try to mitigate natural hazard risks.

		Impact		
		High	Medium	Low
Likelihood	High			
	Medium			
	Low			

Table 1: Risk Impact Matrix

Kadri el al. (2014) examined the impact of natural disasters on infrastructure. Their key findings included the following:

- Natural hazards have serious consequences for critical infrastructure whose failure would have a cascading impact and could lead to catastrophic damage beyond the physical asset itself, adversely affecting people, the environment, and the economy.
- In many places, there is a lack of information about the possible consequences of such disasters, and therefore mitigation measures have not been undertaken.

Urlainis et al. (2014) reviewed the performance of critical infrastructure during several past hazard events, including the 2011 earthquake in Japan and the 2005 hurricane in the United States. Their key findings included the following:

- Lack of robustness in infrastructure was found for all events.
- Examples of insufficient resilience were noted after the events.
- Lack of redundancy was noted, affecting recovery in the aftermath of the natural disasters.

In summary, natural disasters are frequent events with a high impact. Critical infrastructure suffers more pronounced consequences from natural hazard damage because the consequences of the damage has a cascading effect and propagates downline beyond the infrastructure itself. For example, damage to water or electric system can cause loss of functionality to an undamaged hospital. Unfortunately, most infrastructure in its current state cannot withstand the impact of natural hazards. To address this critical shortcoming, the World Bank Group has sponsored a project to investigate the vulnerability of key infrastructure, mitigation/improvement measures, and the costs that are associated with such improvements. This report summarizes the findings. The scope of this project was limited to high-level evaluation; therefore, in-depth investigations or analyses were not performed. Nonetheless, this project found that mitigation measures are available for key infrastructure, that they can be implemented for a fraction of the capital costs in most cases, and that the resulting risk reduction is significant.

CONTENTS

TABLES

1 INTRODUCTION

Many of the critical infrastructure systems worldwide are in areas that are subject to risk from natural hazards. To help mitigate this risk and the associated vulnerabilities of infrastructure, some engineering solutions have been developed and implemented. The efficacy and costs of these measures are not well documented, however. Furthermore, the successful implementation of these engineering countermeasures depends on more robust design and construction quality-assurance (QA) programs. The World Bank Group has sponsored a high-level project to assess these engineering solutions and the associated costs. As part of this project, a metric is proposed to help evaluate the engineering solutions. This report presents the proposed metric and the evaluation table that are intended for use in this project.

Note: Both metric and English units are used in this report. For reference, following are common conversions:

- Distances
  - 1 foot = 0.305 m
  - 1 inch = 25.4 mm
  - 1 mile = 1.61 km
- Velocity
  - 1 mph (miles per hour) = 1.61 km/h = 0.45 m/sec.
- Flow
  - 1 cfs (ft.^{3}/sec) = 0.0283 m^3/sec.
- Pressure
  - 1 ksi (kip/in.^{2}) = 6.89 MPa

2 SELECTION OF METHOD TO CLASSIFY OPTIONS

Several parameters can be used to characterize the performance of infrastructure systems that are subject to natural hazards. Examples include:

- Damage probability, a measure of the resiliency of the system
- Annualized probability of failure
- Socioeconomic costs, such as impact on stakeholders
- Business interruptions, in days, due to downtime
- Loss of functionality
- Financial impact of repair

This project used the first parameter, damage probability. This selection was based on several factors, including the following:

- Damage and its probability can be estimated from fragility functions. Such analytical functions exist for some infrastructure.
- It is preferable to use one parameter for all infrastructure. This approach promotes uniformity and enables cross comparisons for various systems.
- Damage indices and functions are the most quantifiable parameter and thus have been subject to more rigorous past research.

3 REFERENCE INFRASTRUCTURE TABLE

Table 2 through Table 5 present the damage probability as a resiliency index, summarize the infrastructure improvement, and provide the associated cost matrix. Note the following:

- The supplementary background report lists some of the references that were used to obtain the values that are listed in the tables.
- The data in many of the cells relies on past experience and engineering judgment.
- The presented data is intended to be a representative value. The actual improvements, benefits from such improvements, and costs for such improvements depend on specific applications, site conditions, and many other variables.
- In the baseline (total replacement) cost, the following distribution is assumed: 90% for the capital cost (construction materials and labor) and 10% for the construction quality. Such a breakdown represents aggregate infrastructure but can vary for a specific application and site.
- In the additional improvement cost, the following distribution is assumed: 85% for the capital costs (engineering, construction, materials, and labor) and 15% for the improved construction quality management (inspection, testing, sampling, and record keeping). Such a breakdown represents aggregate infrastructure, but can vary for a specific infrastructure system, application, and site.
- To provide the basis for a relative comparison, the cost parameters have been normalized, meaning that the initial capital cost for an asset (i.e., a component) is set to unity. For example, a brand-new component of a nuclear power plant that actually costs several million U.S. dollars is given a value of 1 for the initial cost vulnerability. This normalization eliminates the cost difference between different localities and for different assets.
- To provide the basis for a relative performance comparison between existing (unimproved) and improved components, the baseline damage probability is set to unity (i.e., the damage probability for unimproved components is conditioned to be 100%). Then the damage probability for improved components is converted to a relative percentage of the baseline damage probability of 100%. For example, for a water treatment plant that has an initial damage probability of x% from a design flood event, a baseline damage probability of 1 is given. A damage probability of y% after improvements are implemented is then converted to the percentage of y/x for normalization. This normalization illuminates the significance of improvements regardless of the baseline vulnerability. This approach eliminates the different intensities that are applied for different hazards and for different infrastructure designs. For the normalization to be effective, only relevant hazards (those with moderate to high impact) were considered. Note that the occurrence probability of each hazard is set to 1 in this study, which means that the occurrence of each hazard is completely conditioned.
- The hazard intensity that was selected is intended to approximately represent the threshold that causes certain damage to components.
- Unless stated otherwise, the improvement costs that are listed are for enhancements to be implemented during the construction of new units. For most applications, the retrofitting improvements and costs are similar. However, for some cases, such as existing on-grade roadways that are subject to earthquakes or liquefaction, the retrofitting cost can be prohibitive, and the risk is not mitigated.
- Applicability of improvement methodology is expressed by E (i.e., existing component/structure) and N (i.e., new component/structure) in the table.

Power Sector																
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost					
							Estimate		Normalized		Baseline			Improvement		
Type	**Hazard**	**Intensity**	**Component**	**Engineering improvement**	**Quality improvement**	**Applicability**	**Baseline**	**Improved**	**Baseline**	**Improved**	**Comp.**	**QA**	**Total**	**Comp.**	**QA**	**Total**
Thermal power plants (coal, gas, oil)	EQ motion	Mw 7 PGA 0.4g	Items and their attachments	Seismic component and anchorage	Construction inspection, testing	E & N	0.25	0.02	1	0.1	0.9	0.1	1.0	0.15	0.05	0.20
	Liquefaction	--	Substrate	Soil improvement Deep foundation	Geotechnical report and testing	E & N	0.30	--	1	--	0.9	0.1	1.0	0.15	0.05	0.20
	Wind	100 mph	Building structures stacks	Stiff braced structures Helical strake	Welding quality control, inspection, testing	E & N	0.40	0.1	1	0.3	0.9	0.1	1.0	0.08	0.02	0.10
	Flood	2- to 3-ft. inundation	Entire facility	Floodwall, sheet piling	Ensure water tight construction, inspection	E & N	0.05	--	1	--	0.9	0.1	1.0	0.02	--	0.02
Hydropower plants	EQ motion	Mw 7 PGA 0.4g	Gateway, lift joints, intake towers	Design for higher event, use proper anchorage and seismic components	Inspection during construction, periodic inspection	E & N	0.7	0.4	1	0.5	0.9	0.1	1.0	0.15	0.05	0.2
	Liquefaction	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large rainstorms, 200- to 500-year flood	Spillways, dam crest overtopping	Increased spillway capacity	Proper drenching, underwater inspection,	E & N	0.1	0.05	1	0.5	0.9	0.1	1.0	0.02	0.01	0.03
Solar farms	EQ motion	Mw 7 PGA 0.4g	Support structure	Adequate anchorage, proper design and bracing	Inspection, maintenance	E & N	0.1	0.02	1	0.2	0.9	0.1	1.0	0.04	0.01	0.05
	Liquefaction	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Wind	100 mph	Uplift support	Proper anchorage support for platform	Ensure tested components uses, perform random sampling	E & N	0.2	0.08	1	0.3	0.9	0.1	1.0	0.12	0.03	0.15
	Flood	--	Pole foundation	If scour concern, use riprap	Periodic maintenance	E & N	--	--	--	--	--	--	--	--	--	--
Wind farms	EQ motion	PGA 1.0g (large event)	Monopole	Use seismically robust unit	Maintenance, obtain manufacturer test and certificates	E & N	0.1	0.08	1	0.8	0.9	0.1	1.0	0.05	--	0.05
	Liquefaction	--	Monopole foundation	Use deep foundations	Inspection during installation	N	0.2	--	1	--	0.9	0.1	1.0	0.25	0.05	0.3 (actual cost can be much higher

Power Sector																
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost					
							Estimate		Normalized		Baseline			Improvement		
Type	Hazard	Intensity	Component	Engineering improvement	Quality improvement	Applicability	Baseline	Improved	Baseline	Improved	Comp.	QA	Total	Comp.	QA	Total
	Wind	Design wind 70 to 100 mph	Blade	Optimize blade configuration Use material with higher fatigue life Conservatism in design	Periodic inspection, report any crack initiation on blades or connections	E & N	0.2	0.1	1	0.5	0.9	0.1	1.0	0.04	0.01	0.05
	Flood	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Nuclear power plants	EQ motion	Large events	Main structures, interior components	Seismic isolation main building, Flexible connections Seismically rated components; pipes, cable racks, etc.	Testing, inspection, construction documentation	N	0.3	0.02	1	0.1	0.9	0.1	1.0	0.04	0.01	0.05
	Liquefaction	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large events	Reactor ground, cooling towers, buildings	Improved dike construction, extreme event flood design	Shutdown drills, document review, including geotechnical, hydrological, and construction documents	E & N	0.1	0.07	1	0.7	0.9	0.1	1.0	0.04	0.01	0.05
Substations	EQ motion	Mw 7 PGA 0.4g	Bushings, switches, circuit breakers	Component anchorage, use of seismic components	Review all test documents, ensure redundancy, spares	E & N	0.8	0.3	1	0.4	0.9	0.1	1.0	0.08	0.02	0.1
	Liquefaction	Mw 7 PGD 300 mm	Switches, elevated components	Deep foundation	Geotechnical report, pile load testing	N	0.6	--	1	--	0.9	0.1	1.0	0.18	0.02	0.2
	Wind	Design wind 70 to 100 mph	Elevated components	More robust components	Testing, inspection	E & N	0.3	0.1	1	0.3	0.9	0.1	1.0	0.15	0.05	0.2
	Flood	2- to 3-ft. inundation	Transformers, buildings, ground mounted equipment	Elevate components	Review construction reports, inspections	E & N	0.1	--	1	--	0.9	0.1	1.0	0.08	0.02	0.1
Transmission and distribution lines	EQ motion	Mw 7 PGA 0.4g	T&D systems	Use seismic components	Periodic inspection	E & N	0.02	0.01	1	0.5	0.9	0.1	1.0	0.02	--	0.02
	Liquefaction	--	Lattice support	Use deep foundation	Construction inspection	N	0.2	--	1	--	0.9	0.1	1.0	0.12	0.03	0.15
	Wind	Design wind 70 to 100 mph	Tower	Use steel, concrete or composite towers Use vibration dampers	Construction inspection, Use tested components	E & N	0.3	0.07	1	0.2	0.9	0.1	1.0	0.15	0.05	0.2
	Flood	--	--	--	--	--	--	--	1	1	0.9	0.1	1.0	--	--	--

Table 2: Improvement of infrastructure resilience evaluation matrix for selected natural hazards, power sector

Transport Sector																	
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost						
							Estimate		Normalized		Baseline			Improvement			
Type	**Hazard**	**Intensity**	**Component**	**Engineering improvement**	**Quality improvement**	**Applicability**	**Baseline**	**Improved**	**Baseline**	**Improved**	**Comp.**	**QA**	**Total**	**Comp.**	**QA**	**Total**
Railways (diesel and electric)	EQ motion	MMI VII to VIII (equiv. PGA = 0.3g)	Bridge pier	Pier jacketing retrofit	Apply higher level of QA (assume (E) is on standard level)	E & N	0.12	0.05	1	0.4	0.9	0.1	1	0.18	0.08	0.25
	Liquefaction	PGD = 12 in.	Tracks/roadbeds	French drainage and drainpipe installation	Apply higher level of QA (assume (E) is on standard level)	E & N	0.16	0.01	1	0.1	0.9	0.1	1	0.32	0.14	0.45
	Wind	PGWS = 90 mph	Railway stations	Roof-wall connection retrofit and Bldg. envelopes replacement	Apply higher level of QA (assume (E) is on standard level)	E & N	0.04	0.03	1	0.7	0.9	0.1	1	0.11	0.05	0.15
	Flood	FID = 3.3 ft.	Fuel/DC substations	Elevation and watertight barrier installation	Apply higher level of QA (assume (E) is on standard level)	E & N	0.03	0.01	1	0.2	0.9	0.1	1	0.36	0.15	0.50

Table 3: Improvement of infrastructure resilience evaluation matrix for selected natural hazards, transport sector

Water Sector																
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost					
							Estimate		Normalized		Baseline			Improvement		
Type	**Hazard**	**Intensity**	**Component**	**Engineering improvement**	**Quality improvement**	**Applicability**	**Baseline**	**Improved**	**Baseline**	**Improved**	**Comp.**	**QA**	**Total**	**Comp.**	**QA**	**Total**
Reservoirs (impounding)	EQ motion	PGA 0.6g	Embankment	Design for higher seismic design forces	Drenching, maintenance	E & N	0.15	0.05	1.0	0.3	0.9	0.1	1.0	0.04	0.01	0.05
	Liquefaction	--	Embankment	Restressed concrete piling	Geotechnical report, inspection during construction and pile driving	E & N	0.2	0.02	1.0	0.1	0.9	0.1	1.0	0.18	0.02	0.20
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large event	Embankment crest	Design for higher freeboard (taller structure)	Maintenance, drenching	E & N	0.2	0.05	1.0	0.3	0.9	0.1	1.0	0.04	0.01	0.05
Reservoirs (storage tanks)	EQ motion	Mw 7 PGA 0.4g	Tank Elevated support	Thicker tanks (ground) Perform seismic design and use larger members and adequate connections (elevated)	Construction inspection, random testing during erection	E & N	0.2	0.02	1	.1	0.9	0.1	1.0	0.04	0.01	0.05
	Liquefaction	--	Tank support	Use pile foundation	Geotechnical testing and pile inspection	N	0.4	0.1	1	0.2	0.9	0.1	1.0	0.45	0.05	0.5
	Wind	Large events	Elevated tank	Design for higher wind force	Keep tank full during storms	E & N	0.2	0.05	1	0.4	0.9	0.1	1.0	0.08	0.02	0.1
	Flood	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Water and wastewater treatment plants	EQ motion	Mw 7 PGA 0.4g	Pumping system	Higher threshold seismic design	Improving anchoring system and introducing seismic protective devices	E & N	0.7	0.4	1	0.5	0.9	0.1	1.0	0.1	0.05	0.15
	Liquefaction	--	Sewage system	Higher threshold for permanent ground displacement	Improving the backfilling	E & N	0.7	0.4	1	0.5	0.9	0.1	1.0	0.15	0.05	0.2
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large event	Pumping system	Elevating	Improve construction quality	E & N	0.5	0.2	1	0.5	0.9	0.1	1.0	0.04	0.01	0.05
Distribution pipes	EQ motion	Mw 7 PGA 0.4g	Joints	Higher threshold in seismic design	Replace joints to flexible joints with higher displacement and rotation capacities	E & N	0.7	0.4	1	0.5	0.9	0.1	1.0	0.15	0.05	0.2
	Liquefaction	Large event	Joints and sections	Higher threshold for permanent ground displacement	Replace the sections and the joints to accommodate very large differential displacement and rotation demand	E & N	0.7	0.4	1	0.5	0.9	0.1	1.0	0.50	0.05	0.55
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large event	Pipelines	Higher threshold for large pipe displacement	Keep the pipes filled with water to mitigate buoyancy effects	E & N	0.2	0.1	1	0.3	0.9	0.1	1.0	0.01	0.01	0.02
Sewage network emissaries	EQ motion	MMI VII to VIII (equiv. PGA = 0.3g)	Pump station	Equipment anchorage retrofit	Apply higher level of QA (assume (E) is on standard level)	E & N	0.56	0.39	1	0.7	0.9	0.1	1	0.22	0.04	0.25

Water Sector																
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost					
							Estimate		Normalized		Baseline			Improvement		
Type	**Hazard**	**Intensity**	**Component**	**Engineering improvement**	**Quality improvement**	**Applicability**	**Baseline**	**Improved**	**Baseline**	**Improved**	**Comp.**	**QA**	**Total**	**Comp.**	**QA**	**Total**
	Liquefaction	PGD	Buried pipe	Soil improvement/compaction	Apply higher level of QA (assume (E) is on standard level)	E & N	-	-	1	0.3	0.9	0.1	1	0.45	0.09	0.55
	Wind	PGWS = 90 mph	WTP building	Roof-wall connection retrofit and Bldg. envelopes replacement	Apply higher level of QA (assume (E) is on standard level)	E & N	0.04	0.03	1	0.7	0.9	0.1	1	0.11	0.03	0.15
	Flood	FID = 3.3 ft.	Pump station	Elevation and watertight barrier installation	Apply higher level of QA (assume (E) is on standard level)	E & N	0.08	0.01	1	0.1	0.9	0.1	1	0.36	0.05	0.40
Water conveyance systems (canals)	EQ motion	PGV 0.5 m/sec PGD 0.15 m	Canal walls	Use reinforced concrete liner	Construction inspection, cylinder testing, rebar placement	N	0.2	0.05	1	0.3	0.9	0.1	1.0	0.18	0.02	0.2
	Liquefaction	Based on small segment of long canal	Canal wall and base	Geomembrane liners, soil densification	Construction inspection, geotechnical testing	N	0.2	0.01	1	--	0.9	0.1	1.0	0.02	0.01	0.03
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large events	Gates and locks	Use proper gates, dry channels adjacent	Periodic maintenance, construction inspection	E & N	0.1	0.02	1	.2	0.9	0.1	1.0	0.12	0.03	0.15
Drainage systems	EQ motion	MMI VII to VIII (PGA or PGV)	Drainpipe	Drainpipe replacement	Apply higher level of QA (assume (E) is on standard level)	E & N	-	-	1	0.3	0.9	0.1	1	0.90	0.15	1.05
	Liquefaction	PGD	Drainpipe	Soil improvement/compaction	Apply higher level of QA (assume (E) is on standard level)	E & N	-	-	1	0.3	0.9	0.1	1	0.45	0.09	0.55
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 4: Improvement of infrastructure resilience evaluation matrix for selected natural hazards, water sector

Roadway Sector																
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost					
							Estimate		Normalized		Baseline			Improvement		
Type	**Hazard**	**Intensity**	**Component**	**Engineering improvement**	**Quality improvement**	**Applicability**	**Baseline**	**Improved**	**Baseline**	**Improved**	**Component**	**QA**	**Total**	**Component**	**QA**	**Total**
Highways (on grade)	EQ motion	PGD 0.5 m	Embankment	Provide geogrid reinforcement	Construction inspection, use of approved material	N	0.1	0.05	1	0.5	0.9	0.1	1	0.08	0.02	0.1
	Liquefaction	--	Embankment	Soil improvement	Geotechnical testing, construction inspection and testing	N	0.1	0.05	1	0.5	0.9	0.1	1	0.04	0.01	0.05
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Landslide	--	Road surface	Add retaining wall, stabilize sloe, shotcrete, soil nails	Construction monitoring	E & N	0.2	0.02	1	--	0.9	0.1	1	0.08	0.02	0.1
Highway bridges	EQ motion	Mw 7 PGA 0.4g	Bridge superstructure, column, foundation	Use CA or Japan seismic design, columns as fuse	Construction inspection, testing, qualify contractors	E & N	0.4	0.05	1	0.2	0.9	0.1	1	0.08	0.02	0.1
	Liquefaction	PGD 250 mm	Bridge foundation	Use pile foundation	Geotechnical testing, construction inspection	E & N	0.3	0.05	1	0.2	0.9	0.1	1	0.18	0.02	0.2
	Wind	Small events	Steel bridge members and connections	Use details with longer fatigue life during bridge design life	Inspection of welded connections, reduce section loss by corrosion prevention	E & N	0.05	0.01	1	0.2	0.9	0.1	1	0.04	0.01	0.05
	Flood	Large floods	Bridge foundation	Use riprap	Hydrological report, construction inspections	E & N	0.05	0.02	1	0.5	0.9	0.1	1	0.04	0.01	0.05
	Landslide	PGD = 14 in., 7 in.	Bridge foundation	Soil improvement	Apply Higher level of QA (assume (E) is on Standard level)	E & N	0.5	0.16	1	0.3	0.9	0.1	1	0.14	0.02	0.15
Secondary urban roads (on grade)	EQ motion	Mw 7 PGA 0.4g	Road surface and underlying material	Provide seismic reinforcement, compact the underlying material	Use earthquake resistance foundations	N	0.1	0.05	1	0.5	0.9	0.1	1	0.04	0.01	0.05
	Liquefaction	Large PGD: more than 0.3 m	Road surface and underlying material	Provide reinforcement against large ground displacement	Soil improvement, avoid areas subjected vulnerable to liquefaction	N	0.1	0.05	1	0.5	0.9	0.1	1	0.04	0.01	0.05
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large floods	Road surface	Provide barriers, improve drainage	Construction inspection, testing, qualify contractors	E & N	0.1	0.05	1	0.5	0.9	0.1	1	0.02	0.01	0.03
	Landslide	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Urban (roadway) bridges	EQ motion	Mw 7 PGA 0.4g	Bridge superstructure, abutments, footings	Use CA or Japan seismic design, columns as fuse	Construction inspection, testing, qualify contractors	E & N	0.35	0.04	1	0.2	0.9	0.1	1	0.15	0.05	0.2

Roadway Sector																
	Natural hazard		Critical system/component				Damage probability (resiliency index)				Normalized cost					
							Estimate		Normalized		Baseline			Improvement		
Type	**Hazard**	**Intensity**	**Component**	**Engineering improvement**	**Quality improvement**	**Applica bility**	**Baseline**	**Improved**	**Baseline**	**Improved**	**Com pone nt**	**QA**	**Total**	**Comp onent**	**QA**	**Total**
	Liquefaction	PGD 250 mm	Bridge foundation	H pile or pre-stressed pile foundation	Geotechnical testing, construction inspection	E & N	0.4	0.1	1	0.2	0.9	0.1	1	0.25	0.05	0.3
	Wind	Small events	Connection of diaphragms to steel girders	Reduce dissertation-induced fatigue cracking, redundant non-fracture critical design	Inspection of welded connections, reduce section loss by corrosion prevention	E & N	0.1	0.03	1	0.3	0.9	0.1	1	0.04	0.01	0.05
	Flood	Large events	Pier and abutment foundations	Mitigation of local scour, use rocks or pier walls	Regular inspection, construction quality control	E & N	0.03	0.02	1	0.7	0.9	0.1	1	0.01	0.01	0.01
	Landslide	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Unpaved tertiary roads	EQ motion	Mw 7 PGA 0.4g	Road surface and underlying material	Provide seismic reinforcement, compact the underlying material	Use earthquake resistance foundations	N	0.1	0.05	1	0.5	0.9	0.1	1	0.08	0.02	0.1
	Liquefaction	Large PGD: more than 0.3 m	Road surface and underlying material	Provide reinforcement against large ground displacement	Soil improvement, avoid areas subjected vulnerable to liquefaction	N	0.1	0.05	1	0.5	0.9	0.1	1	0.04	0.01	0.05
	Wind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Flood	Large floods	Road surface	Provide barriers, improve drainage	Elevate the roads	E & N	0.1	0.05	1	0.5	0.9	0.1	1	0.02	0.01	0.03
	Landslide	--	Road surface	Add retaining wall, stabilize slope, shotcrete, soil nails	Construction monitoring	E & N	0.2	0.02	1	--	0.9	0.1	1	0.03	0.02	0.05
Wooden bridges	EQ motion	Acceleration = 0.4g	Wood bridge trusses	Truss strengthening & connection retrofit	Apply Higher level of QA (assume (E) is on Standard level)	E & N	0.35	0.03	1	0.1	0.9	0.1	1	0.18	0.03	0.20
	Liquefaction	PGD = 10 in.	Bridge foundation	Pile addition (foundation retrofit)	Apply Higher level of QA (assume (E) is on Standard level)	E & N	0.44	0.13	1	0.3	0.9	0.1	1	0.27	0.04	0.30
	Wind	Connection fatigue category	Truss connections	Connection retrofit/replacement	Apply Higher level of QA (assume (E) is on Standard level)	E & N	0.15	0.05	1	0.3	0.9	0.1	1	0.09	0.02	0.10
	Flood	Flood return period (1,000 to 100 yr.)	Foundation ground	Scour mitigation by ground strengthening (riprap, rock, etc.)	Apply Higher level of QA (assume (E) is on Standard level)	E & N	0.06	0.02	1	0.3	0.9	0.1	1	0.03	0.00	0.03
	Landslide	PGD = 14 in., 7 in.	Bridge foundation	Soil improvement	Apply Higher level of QA (assume (E) is on Standard level)	E & N	0.63	0.25	1	0.4	0.9	0.1	1	0.23	0.03	0.25

Table 5: Improvement of infrastructure resilience evaluation matrix for selected natural hazards, roadway sector

4 REFERENCES

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