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EARTHQUAKE RISK MODELLING AND DISASTER RESILIENCE PLANNING AT THE COMMUNITY LEVEL

Murray Journeay
Research Scientist, Geological Survey of Canada, Canada
Murray.Journeay@NRCan-RNCan.gc.ca

Fiona Dercole
Section Head, Public Safety, District of North Vancouver, Canada
DercoleF@dnv.org

ABSTRACT: This study describes the likely impacts of a significant earthquake in the Cascadia region of southwestern British Columbia, and actions that might be considered to reduce future losses. Target criteria include a system of performance measures that track current and future conditions of risk in terms of building performance, public safety, lifeline resilience and economic security. We use a Canadian adaptation of the Hazus loss estimation methodology to assess damages and losses for a plausible earthquake scenario in the Strait of Georgia (M7.3), and probabilistic risk assessment capabilities of the Global Earthquake Model to develop a more synoptic profile of who and what are vulnerable to known earthquake hazards in the Cascadia region. Study outputs provide a capacity to explore thresholds of risk tolerance and mitigation strategies through ongoing emergency planning and land use decision-making activities at the community level. Methodologies and insights gained through this study are transferrable to other communities who may face similar challenges of managing growth and development in areas exposed to earthquake hazards. The study contributes to broader efforts led by the Canadian Safety and Security Program to develop an all-hazard risk assessment framework to support disaster resilience planning at a national scale.

1. Introduction

The societal costs of natural perils are steadily rising in Canada due to increased demands for urban development in hazard prone areas, an aging and increasingly vulnerable system of critical infrastructure, and limited capacities of communities to anticipate and plan for unexpected disasters. Lessons learned from recent earthquake events around the world underscore the need for a comprehensive risk-based approach to land use planning and emergency management at all levels of government.

Canada does not yet have a comprehensive framework for managing risks associated with growth and development in areas exposed to earthquake hazards. National building codes incorporate seismic design guidelines to ensure public safety for new buildings (NBCC, 2010). However, building code guidelines do not address seismic risk concerns for older buildings constructed prior to the mid-1970s, or the broader range of impacts and consequences that are relevant for emergency management and comprehensive land use planning. These include a range of performance measures such as physical damage and loss of functionality (building performance); the number of injuries and extent of social disruption (public safety); loss of utility services (lifeline resilience); and expected financial losses with and without mitigation measures in place (economic security).

This study addresses the need for improved methods and capabilities for earthquake risk assessment and disaster resilience planning at the community level. We explore the realm of earthquake risk at a scale that is relevant for municipal planning and policy development, and validate a framework for integrated assessment and scenario modelling that is designed to help guide risk reduction and disaster resilience planning activities at local and regional scales. Motivating questions for our work include:

- Who and what are most vulnerable to known earthquake hazards in the region?
- What are the underlying socioeconomic drivers of risk and what can we expect if a major earthquake were to occur in the near future?
- How might this information be used to inform mitigation and adaptation planning activities that are effective in reducing future losses and building disaster resilience?

2. Integrated Risk Assessment

Risk-based planning is about managing opportunities for growth and development in ways that minimize potential future losses, and that promote longer-term community resilience. It requires a common understanding of the risk environment, and the development of strategies that are framed by policy goals, informed by scientific knowledge, and tempered by the need to make practical choices between diverse and often competing social values and preferences.

We have implemented a framework for integrated risk assessment that has been specifically developed to support disaster risk reduction planning at the community scale in Canada (Journeay, 2015). The framework is built around a system of target criteria and related indicators that are used to transform knowledge about earthquake risks into actions that can be taken in advance of a disaster to reduce vulnerabilities and increase community resilience through investments in mitigation, emergency management and adaptation (See Fig.1).

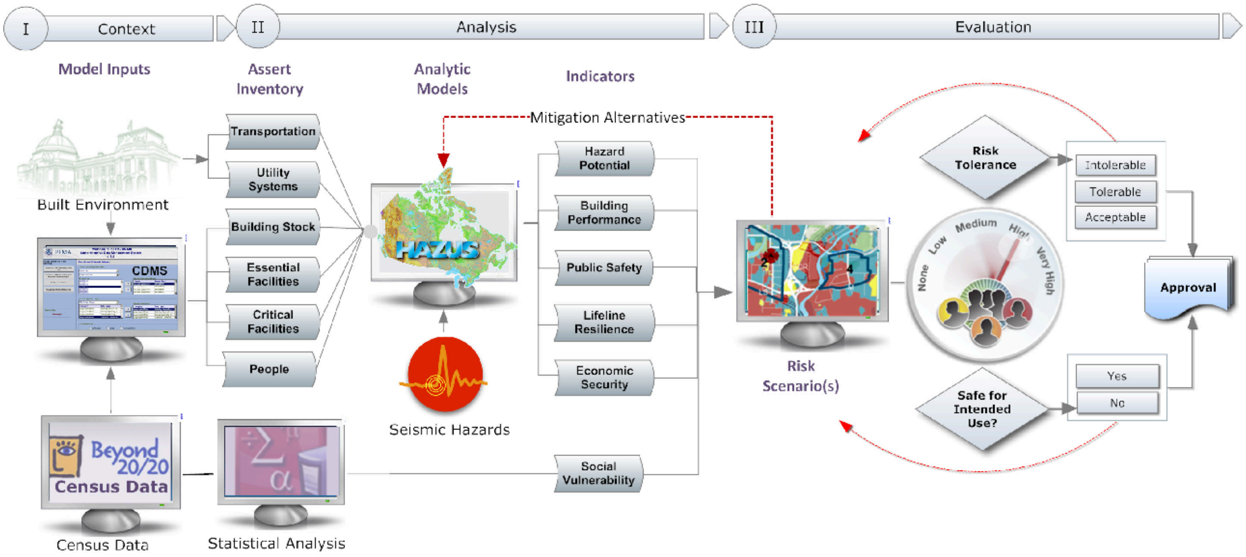


Fig. 1 – A Framework for integrated risk assessment and scenario planning (Journeay, 2015).

2.1. Risk Analysis

The analytic component of the framework is focussed on generating knowledge about the potential impacts and consequences of a hazard threat based on direct observation and experience from past events (risk appraisal), and/or indirect measurement using quantitative modes of scenario- and probability-based analysis (risk modelling). The choice of analytic methodology is based on overall goals and objectives of the planning process.

Scenario-based methods of analysis are used to measure damage potential, expected losses and loss statistics for a collection of assets exposed to seismic hazards associated with a specific earthquake event. They help planners anticipate what to expect in the event of a major earthquake, and provide a basis for prioritizing actions that might be considered to increase disaster resilience through mitigation and adaptation. We use a Canadian version of the Hazus loss estimation methodology (NIBS, 2002; FEMA, 2004; 2011) to analyze cause-effect relationships for plausible earthquake scenarios, and to evaluate risk reduction potential through investments in structural mitigation.

Probability-based methods of risk analysis are used to measure the cumulative profile of loss and loss statistics for assets that are exposed to all known seismic hazards for a given region and time horizon of interest. They provide a synoptic assessment of who and what are vulnerable to known earthquake hazards, and are used in evaluating thresholds of risk tolerance over time horizons that are relevant for comprehensive land use planning and policy development. Cumulative risk profiles for this study were developed using OpenQuake – an open source risk modelling platform that incorporates state-of-the-art methods for both classical and event-based probabilistic analysis of earthquake hazards (Silva *et al.*, 2013).

2.2. Scenario Modelling and Risk Evaluation

Scenario-based modelling is an effective way of integrating science into the decision making process. It helps establish a shared understanding of the risk environment, and offers a structured framework for exploring the strengths and weaknesses of policy alternatives using a combination of maps and target indicators. Target indicators are used to measure existing conditions of risk, and to evaluate policy choices that seek to reduce underlying vulnerabilities and increase community resilience through mitigation, emergency management and adaptation. They express intent with respect to a desired set of outcomes and provide a framework for exploring thresholds of risk tolerance. Risk metrics for this study include:

- **Seismic Hazard Potential:** the intensity of shaking and potential for ground failure at any given location as a result of seismic energy generated by an earthquake event.
- **Building Performance:** the likelihood of damage (resistance) and the estimated time to restore functionality to homes and businesses after a major earthquake (recovery).
- **Public Safety:** the likelihood of injury or death from earthquake damages, and the extent of social disruption caused by loss of habitation and business interruption.
- **Social Vulnerability:** intrinsic characteristics of a community (population & demographics) that may contribute to unsafe conditions and that have a potential to amplify the negative impacts and consequences of a disaster event.
- **Lifeline Resilience:** the capacity of utility and transportation systems to withstand and recover from the impacts of a major earthquake.
- **Economic Security:** expected capital and income-related losses resulting from a major earthquake and the benefits of investing in mitigation and/or adaptation measures.

The system of indicators extends the scope of seismic safety thresholds used to inform design guidelines in the National Building Code of Canada (NBCC, 2010), which are based primarily on ground shaking intensity (hazard potential). The indicators also provide a capability to evaluate whether existing or planned activities meet regulatory guidelines and are considered “safe for the intended use”; and whether they are consistent with what the community considers a “tolerable threshold of risk.” Planning scenarios that meet these minimum thresholds are advanced for further policy analysis and the selection of actionable strategies that can be implemented within the limits of available resources. Planning scenarios that fail to meet these minimum thresholds are revised by adjusting seismic design measures to increase the performance of selected target criteria, or by re-negotiating levels of risk that the community is willing to live with (Fig. 1).

3. Disaster Risk Reduction – A Case Study

The Cascadia region of southwestern British Columbia is one of the most seismically active regions in Canada (Cassidy *et al.*, 2010). Smaller earthquakes occur daily and the region is known to have experienced some of the largest earthquakes ever recorded. Though infrequent, these larger earthquakes have the potential for catastrophic losses and pose an imminent and credible threat to settled areas in the Pacific Northwest regions of British Columbia and Washington State.

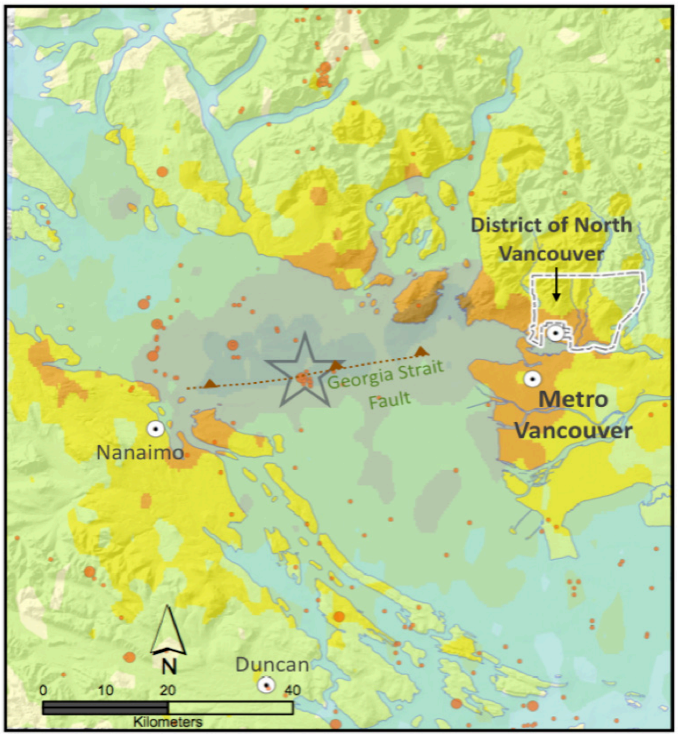
A recent study commissioned by the Insurance Bureau of Canada reveals that losses associated with a major earthquake in southwest British Columbia could exceed $75 billion (AIR Worldwide, 2013). The Lower Mainland region of Metro Vancouver and the Fraser Valley are exposed to a wide range of seismic hazards including severe ground shaking, liquefaction, earthquake-triggered landslides and tsunami. All have the potential to cause catastrophic damage, loss of life and financial hardship. Areas at greatest risk include older neighbourhoods and commercial/industrial districts in downtown Vancouver, Richmond, Delta, Annacis Island and North Vancouver.

This study examines earthquake risks for the District of North Vancouver (DNV) — an urban municipality of approximately 83,000 people situated along the North Shore Mountains and marine waterfront areas of Burrard Inlet (See Fig. 2). It includes a detailed analysis of what to expect in terms of impacts and consequences should a major earthquake occur at some point in the near future, and provides insights on actions that might be considered to increase disaster resilience of the community over time.

3.1. The Scenario Earthquake

On June 24, 1997, an earthquake measuring M4.6 was triggered by displacement along a shallow crustal fault in the Strait of Georgia – midway between Nanaimo and Metro Vancouver. The earthquake was preceded by a M3.4 foreshock event on June 13, and by numerous small aftershock events. There have been six other significant earthquakes in this same zone of active seismicity over the past 40 years (Cassidy *et al.*, 2000). The largest of these was a M4.9 earthquake in 1975 that was accompanied by a strong aftershock sequence.

In the following sections, we consider what might be expected if the Georgia Strait Fault were to rupture again with a displacement capable of causing a M7.3 earthquake (See Fig. 2). Ground motion intensities are sufficient to cause significant damage and associated socioeconomic losses that would likely test local capabilities for response, but that would not overwhelm the community with respect to longer-term economic recovery. However, it is not a worst-case scenario when compared with lower probability earthquakes hazards that are known to occur in the region.



MMI	IX	VIII	VII	VI
PGV (cm/sec)	60-178 (86)	30-60 (41)	14-30 (20)	7-14 (9.6)
PGA %g	55-139% (40)	29-55% (40)	16-29% (22)	9-16% (12)

Fig. 2– Ground motion model for a M7.3 earthquake scenario in the Strait of Georgia.

3.1.1. Ground Shaking

The scenario event is representative of a class of >M7 shallow crustal earthquakes that have occurred in the Georgia Basin region over the past ~500 years (Hyndman *et al.*, 2003). Ground motion models were generated in OpenQuake on the basis of reverse slip along a WSW-trending fault zone with a dip of ~50 degrees to the NNW (Cassidy *et al.*, 2000). Predicted ground shaking intensities vary considerably across the study area as a function of distance from the earthquake epicentre, geologic setting and the effects of local site amplification. Peak ground velocities (PGV) within the District of North Vancouver are expected to range from 6.4 cm/second in highland areas underlain by solid bedrock — to a maximum of 48.1 cm/second in lowland areas along the waterfront that are underlain by glacio-fluvial sediments and anthropogenic infill deposits.

3.1.2. Ground Failure

Liquefaction is expected to occur in areas underlain by water-saturated soils that would lose cohesion during intense ground shaking. Areas underlain by landfill deposits along the waterfront are of greatest concern (sand, gravel and crushed rock), with lateral displacements that are estimated to be up to a metre and in some places greater than two metres. Other areas of concern include delta and outwash terrace deposits of sand and gravel in the lower Capilano and Seymour valleys, where lateral displacements are 30-60 cm.

Earthquake-triggered landslides are localized along steep unstable slopes where severe ground shaking results in forces that are strong enough to overwhelm the internal shear strength of surficial materials and the gravitational forces that hold them in place on the hillside. Hotspots of concern coincide with areas of previous landslides, and include steep valley walls and preserved outwash terraces along the Capilano River, Mackay Creek, Mosquito Creek, Lynn Creek and the Seymour River.

3.2. Risk Reduction Potential

We have used methods of integrated risk assessment to explore the effectiveness of investing in seismic retrofit measures aimed at reducing the vulnerability of older buildings in commercial/industrial zones that are susceptible to significant damage and capital losses in the event of a major earthquake. The analysis compares expected losses for baseline conditions and a mitigation scenario in which vulnerable homes and businesses have been seismically retrofitted to current seismic design standards through an ongoing community development process.

The costs of mitigation are estimated to be 2-3% of the total replacement value based on empirical data from seismic retrofit programs that have been implemented in California (Porter *et al.*, 2006; City and County of San Francisco, 2010). Average mitigation costs range from $12,000 dollars for a typical residential wood frame building to ~$50,000 dollars for concrete and masonry structures that are common in higher density mixed-use town centres and older commercial/industrial precincts along the waterfront. The benefits of mitigation were analyzed for each building in the portfolio based on losses avoided across a spectrum of target criteria and related performance measures. In addition to reductions in capital and income-related losses for homes and businesses (*Economic Security*), we also assessed mitigation benefits in terms of increased structural resistance to earthquake damages and corresponding reductions in the amount of time required to restore baseline levels of functionality (*Building Performance*); reductions in the number of people likely to sustain life-threatening injuries, the extent of social disruption in the community (*Public Safety*); and reductions in utility service disruptions (*Lifeline Resilience*). Risk reduction potential is summarized in Figures 3 and 4.

3.2.1. Economic Security

Direct economic losses for the scenario earthquake are estimated to be ~$3 billion dollars, with capital losses of nearly $2.3 billion, and an additional $645 million in lost revenue caused by business disruption in the weeks and months following the earthquake. The profile of loss is skewed by the vulnerability of older concrete and unreinforced masonry buildings in commercial/industrial zones along the waterfront that are exposed to severe ground shaking and liquefaction spreading. The mean loss ratio for residential homes in the scenario earthquake is ~13%, which translates into an average capital loss of ~$66,000 for a single-family residence and ~$345,000 for multi-family apartment and condominium complexes. The mean loss ratio for business assets is significantly higher with expected average capital losses of $360,000 for commercial buildings and up to $500,000 for industrial facilities. As a result, the business sector is expected to bear the largest burden of financial risk with a potential for up to 90% loss in gross daily revenue. This translates into nearly $4.4 million dollars of income-related losses every day across the business sector for the duration of the recovery process. Prolonged business disruption at this level would have a substantial and lasting impact on economic vitality in the broader Metro Vancouver region.

Investments in seismic retrofits have the potential to reduce capital losses by ~ $160 million dollars and income-related losses by more than $610 million dollars in the District. The greatest efficiencies are gained in retrofitting older concrete, unreinforced masonry and pre-cast structures in commercial/industrial areas along the waterfront. As a result, business disruption and related losses are reduced by 95%, thereby promoting economic security and overall resilience. As expected, the economic benefits are greatest for vulnerable buildings (precast, reinforced masonry and manufactured structures, etc.) that do not conform to modern design guidelines for seismic safety. Benefit-cost ratios for each of these building classes are quite variable on a site-by-site basis with mean values that range from a low of 2 for wood frame structures to ~4 for more vulnerable concrete and masonry structures. The most significant return on investment is on individual buildings in commercial/industrial centres along the waterfront, where the benefits of mitigation outweigh costs by as much as 11 to 1.

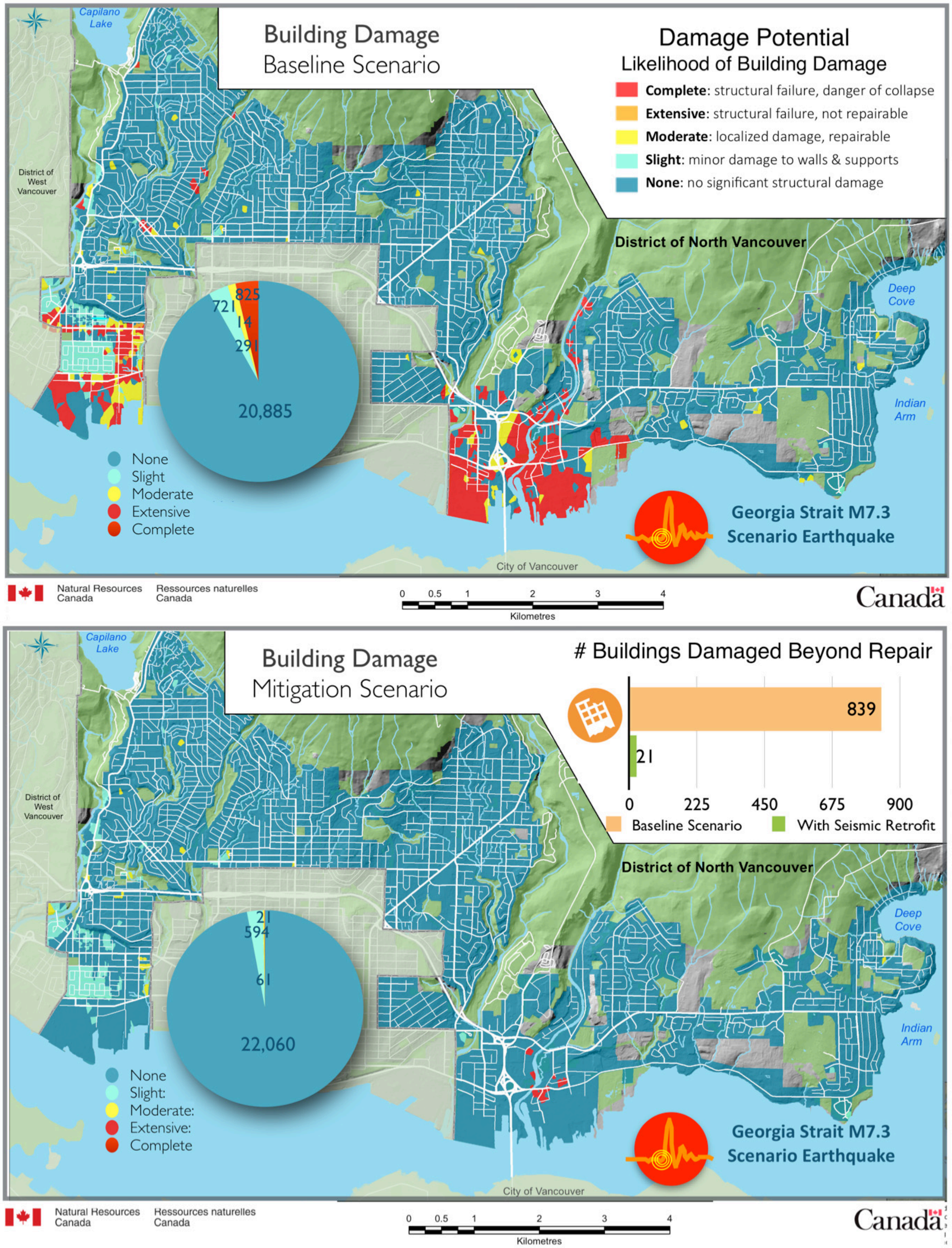


Fig. 3 – Maps and charts showing expected patterns of building damage for the Georgia Strait M7.3 scenario earthquake, with and without seismic retrofit measures in place.

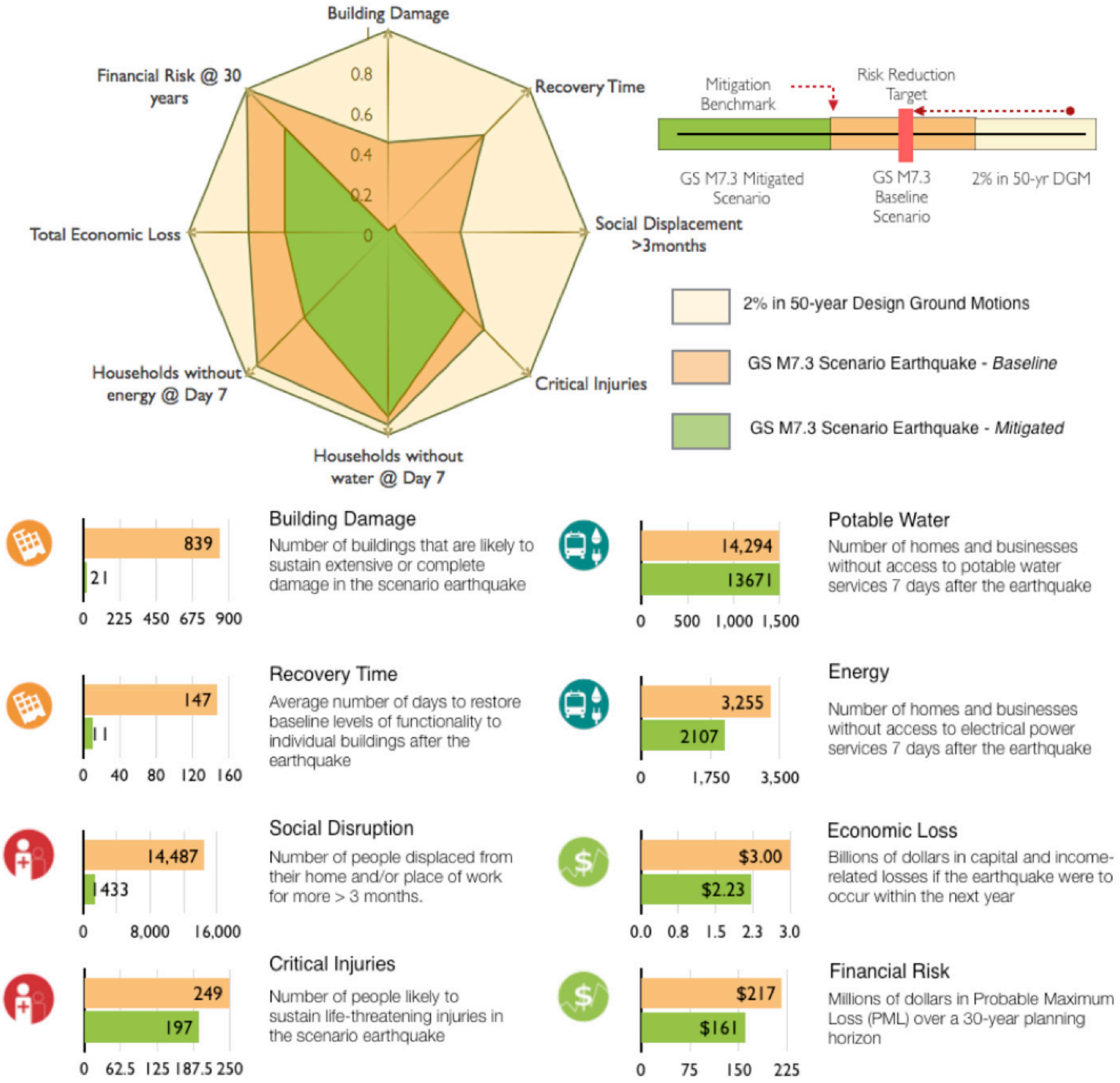


Fig. 4 – Indicator charts summarizing risk reduction potential through structural mitigation.

3.2.2. Building Performance

Building performance directly influences the safety and security of individuals, the extent of social disruption following an earthquake, and the longer-term economic security of a community. Key performance measures include the number of structures likely to sustain extensive and/or complete damage (resistance), and the number of days needed to restore baseline levels of functionality (recovery) for both baseline and mitigation scenarios.

For current baseline conditions, It is estimated that ~840 buildings would sustain extensive or complete damage in the Georgia Strait M7.3 scenario earthquake. The majority of these are older concrete and unreinforced masonry structures in business precincts along the waterfront (~600 buildings), More than 215 residential structures and 25 public sector buildings are also likely to be damaged beyond repair in isolated hotspots of severe shaking and ground failure throughout the District.

Specific measures that might be considered to increase building performance include: the strengthening of foundation connections; bracing and/or anchoring of frame, floor and roof systems; the addition of shear walls; and a variety of other measures to help dissipate seismic energy and resist the effects of shear and lateral drift. With mitigation measures in place, all but 21 of the 839 buildings currently exposed to extensive or complete damage from a major earthquake would be preserved from significant damage (Figure 3). Fifteen of the buildings still in danger of collapse are situated along the industrial waterfront with the remaining six in surrounding commercial precincts. Nearly all are larger unreinforced masonry buildings that are likely to collapse from severe ground shaking and lateral spreading caused by liquefaction.

Investments in seismic retrofits to the most vulnerable buildings in the District also have the effect of reducing recovery times for homes and businesses. The greatest gains are in the residential sector, where mean recovery times are reduced by almost 95% (See Fig. 4). Recovery times are reduced by ~4 months for single-family homes and over one year for multi-family residential buildings that have been seismically retrofitted. Recovery times are reduced ~4 months for commercial and industrial buildings, and ~1 week for public sector buildings.

3.2.3. Public Safety

Investments in seismic retrofits have the potential to reduce the number of people expected to sustain or succumb to life-threatening injuries for a daytime earthquake scenario by 52 (Fig. 4). The greatest gains are for older concrete and unreinforced masonry buildings, where safety performance levels increase by 17% and 28%, respectively. While this represents a significant reduction in the number of potential fatalities, more than 1,300 people will still sustain injuries that require paramedic care and ~425 will need emergency medical care at a hospital — even with mitigation measures in place.

Although most of the population is likely to shelter in place, it is expected that more than 3,000 residents would likely be displaced from their homes for up to 20 days after the scenario earthquake to allow time for building inspections and restoration of lifeline services. While the majority of those displaced will seek temporary accommodation with friends and family, several hundred people would require emergency shelter and social services from local authorities and supporting aid agencies. Seismic retrofit measures are most effective in reducing the extent of social disruption for those displaced three months or more (See Fig. 4). More than 13,000 people who would otherwise be displaced by the earthquake are expected to return to their homes and places of work with mitigation measures in place. The most significant reductions in social disruption are for residents displaced more than a year (~1,500 people), and for employees displaced for 3 months or more (~16,500 workers).

3.2.4. Lifeline Resilience

Lifeline resilience measures the extent to which critical infrastructure systems can absorb the impacts of sudden shocks that threaten structural coherence and functional integrity, and the capability of these systems to provide access to essential services during the recovery process. Target criteria are expressed in terms of performance measures that track the number of system components that are expected to remain functional following a major earthquake (resistance), and the number of days required to restore water and power services to the community (recovery).

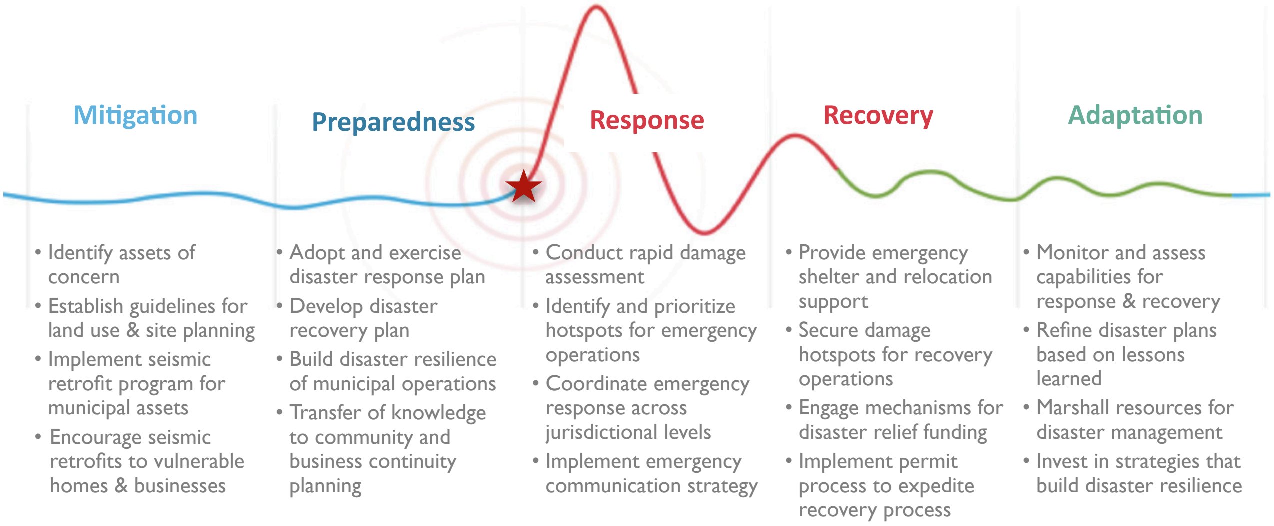
Water utilities and related lifeline services are particularly vulnerable to earthquake damage and loss of functionality in areas of severe ground shaking, and in older neighbourhoods where pipelines are constructed of older brittle materials that are less resistant to settling and lateral displacements caused by earthquake-triggered liquefaction. Earthquake damages are expected to result in leaks and breaks that would require at least 100 repairs to restore potable water service, and ~250 repairs to restore functionality for wastewater infrastructure. For current conditions, it is estimated that more than half of all homes and businesses would be without water for up to 7 days after the earthquake. Depending on the size and capacity of repair crews, it would take up to 18 days to restore full service capacity. Nearly 700 homes and businesses that would otherwise be without services would have access to potable water within 7 days as a result of investments in seismic retrofits to pipelines and water facilities. In addition, the time required to restore full service capacity is likely to be reduced by one week or more. This represents a ~ 40% increase in service capacity for potable water systems and a ~70% increase for wastewater systems.

Our assessment of power system resilience is limited to an analysis of damages to electrical substations within the District and does not account for upstream dependencies on power generation or distribution. Electrical facilities are expected to sustain a ~50% drop in service capacity with as many as 18,000 homes and businesses without access to power immediately after the earthquake and ~3,500 without power one week later. Investments in seismic retrofits to vulnerable facilities have the potential to increase overall system resistance with ~7,000 fewer service interruptions immediately after the earthquake, and a significantly shorter amount of time to restore full service capacity to the community. Gains in system resilience have important implications on business interruption and overall economic security during the recovery process.

4. From Knowledge to Action

Disaster resilience is a forward-looking process of planning through which knowledge about the risk environment is transformed into actions that have potential to reduce intrinsic vulnerabilities and increase the capacities of a community to withstand, respond to and recover from unexpected hazard events. The aim is to marshal the resources and capabilities needed to realize policy goals for growth and development (opportunities) while minimizing the potential negative impacts of hazards that can undermine the longer-term sustainability of a community or region (risks and liabilities).

Outputs of this study have been used to inform the development of an earthquake action ready plan for the District of North Vancouver (Fig. 5). The plan was developed by District staff and is aligned with risk reduction guidelines of the UN Disaster Resilience Cities Program (UNISDR, 2012). It is intended to help increase capacities of the District to reduce future losses and become more resilient to earthquake hazards through strategic investments in mitigation, emergency management and adaptation planning.



Mitigation
- Identify assets of concern
- Establish guidelines for land use & site planning
- Implement seismic retrofit program for municipal assets
- Encourage seismic retrofits to vulnerable homes & businesses

Preparedness
- Adopt and exercise disaster response plan
- Develop disaster recovery plan
- Build disaster resilience of municipal operations
- Transfer of knowledge to community and business continuity planning

Response
- Conduct rapid damage assessment
- Identify and prioritize hotspots for emergency operations
- Coordinate emergency response across jurisdictional levels
- Implement emergency communication strategy

Recovery
- Provide emergency shelter and relocation support
- Secure damage hotspots for recovery operations
- Engage mechanisms for disaster relief funding
- Implement permit process to expedite recovery process

Adaptation
- Monitor and assess capabilities for response & recovery
- Refine disaster plans based on lessons learned
- Marshall resources for disaster management
- Invest in strategies that build disaster resilience

Fig. 5 –Earthquake Action Plan for the District of North Vancouver. Modified from (Keller and Schneider, 2014).

4.1. Mitigation

Mitigation is focused on measures that can be implemented before a disaster event to reduce the physical vulnerability of people and critical assets and the potential for socioeconomic losses. Structural mitigation involves retrofitting core elements of a building or engineered structure to increase physical resistance to seismic loads and lateral displacements caused by severe shaking and/or ground deformation. Non-structural mitigation includes measures that minimize the exposure of people and physical assets to known earthquake hazards through land use policies, development restrictions (permits, bylaws, etc.), early warning systems, and the physical retrofitting of non-skeletal building elements (facades, internal partitions, contents, machinery and utility systems).

4.2. Emergency Management

Emergency management embraces the full spectrum of preparedness planning and operational activities that are taken both during and after a disaster to ensure the safety and security of people and critical assets. Emergency preparedness activities are designed to increase awareness, self-reliance, and response capabilities of individuals and communities. They include continuity planning for homes and businesses to minimize levels of disruption during the recovery process; risk transfer and disaster relief funding to minimize the longer-term socioeconomic consequences of a disaster; land use policies that direct the re-building and ongoing development of communities in ways that minimize exposure to earthquake hazards; and governance models that build on effective public-private partnerships to streamline the process of recovery and re-building.

4.3. Adaptation

Adaptation encompasses a wide range of actions that are planned in advance but implemented after a disaster event to increase the capacities of people, buildings, and engineered systems to respond and recover from the impacts and consequences of a major earthquake. Resilient systems experience relatively small levels of disruption and are likely to recover baseline levels of performance in a relatively short period of time. In some cases these systems may even increase overall performance due to adaptive design and reorganization during the recovery period. Systems characterized by low levels of resilience experience a relatively large drop in performance following a disaster, take a longer period of time to recover, and may never regain pre-event levels of functionality. The window of opportunity for implementing adaptation measures following a disaster event is often small and quickly crowded with diverse and often competing public policy issues. The key is to identify those actions with the greatest potential to effect change during the recovery process, and to marshal resources and capabilities that will be required to implement these measures when the time comes.

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