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1.7 EARTHQUAKES

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DRRPathways.ca

RESILIENCE PATHWAYS

CO-CREATING NEW KNOWLEDGE FOR UNDERSTANDING RISK AND RESILIENCE IN BC

This article is part of the Resilience Pathways Report. The report has the following objectives: a) to share knowledge about existing practices and recent advances in understanding and managing disaster and climate risk in BC, including some information on relevant federal programs, and b) to provide insights on gaps and recommendations that will help build pathways to resilience in BC.

This article belongs to *Chapter 1 Understanding and Managing Climate and Disaster Risk: Hazard Threat*. To read all articles in the report, see DRRPathways.ca.

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1.7 EARTHQUAKES

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ABOUT EARTHQUAKES

Earthquakes can occur almost anywhere, but they are primarily located along tectonic plate boundaries, where pieces of the earth's crust rub against one another. In BC, tectonic plate boundaries include the Cascadia Subduction Zone and the Queen Charlotte Fault offshore of Haida Gwaii. Earthquakes occur along these boundaries and also in the subducting Juan de Fuca slab, the deep portion of the Cascadia Subduction Zone, and as relatively shallow earthquakes in the North American plate. The earthquake hazard is generally higher in coastal areas of BC. Damaging earthquakes do not occur frequently in BC, but when they happen, impacts can be extremely damaging and widely felt.

DESCRIPTION

Large, damaging earthquakes are part of the overall earthquake threat in BC and can impact people, structures, infrastructure, and cultural and environmental sites. On average, there are several thousand earthquakes recorded in BC annually (Figure 1), of which approximately 50 earthquakes are felt. Three types of earthquakes can occur in Southwest BC: 1) large megathrust earthquakes along the plate boundary off Vancouver Island with magnitudes up to about 9.0; 2) deep intraslab earthquakes with magnitudes up to about 7.5, and 3) shallow crustal earthquakes with magnitudes up to about 7.5.

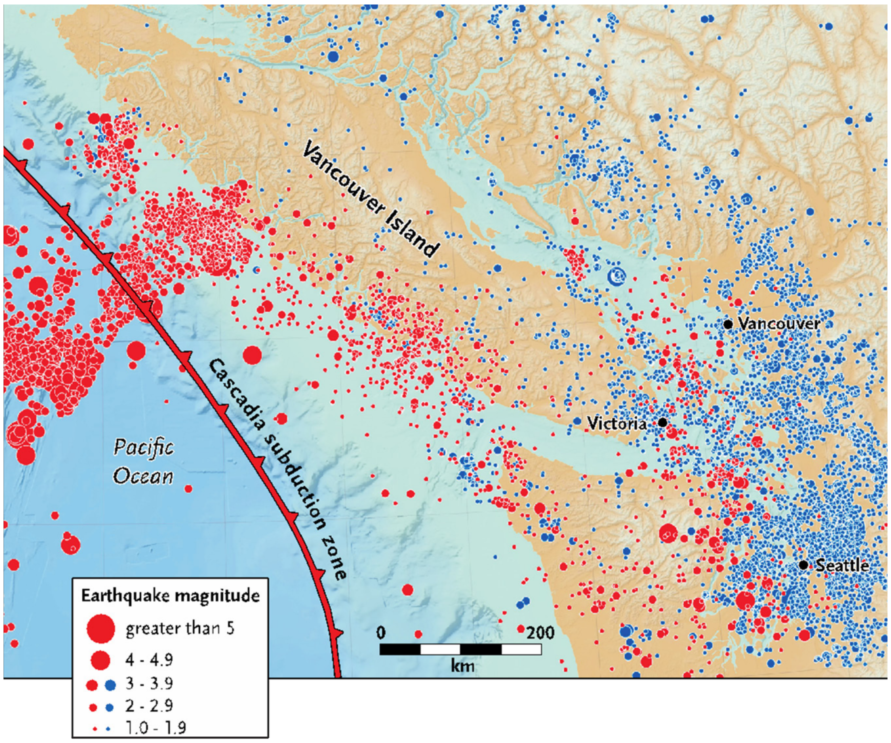

Figure 1: Distribution of recorded earthquakes (Graphic: Natural Resources Canada).

When a fault ruptures, seismic waves are propagated through the earth, causing the ground to shake. This shaking causes buildings or infrastructure to vibrate, potentially becoming damaged or collapsing. Intense ground shaking can last from seconds to minutes and may be followed by numerous aftershocks. Secondary effects can include landslides, liquefaction, floods, and fires. In addition, aftershocks, particularly from shallow crustal and megathrust earthquakes, are of concern as they exacerbate the impacts. Damage to critical infrastructure can cause disruption of services and have indirect impacts on lives, livelihoods, and the economy. Damage to industrial facilities from earthquake shaking can lead to cascading impacts such as release of chemical hazard substances that harm human health and the environment.

Tsunamis can be triggered by local and distant earthquakes. If the earthquake triggers land or submarine slides, these can create tsunami waves. Combined with sea level rise, this can put some communities in coastal areas at higher risk.

With the increase in intensity and frequency of hydrometeorological events, such as floods, wildfires, and extreme temperatures, there is a greater likelihood that a damaging seismic event will be followed by a meteorological hazard that intensifies the impact of the initial event. Sea level rise makes the impacts of coseismic subsidence and tsunamis more severe.

IMPACT ON BUILDINGS

BC has the highest concentration of assets at earthquake risk in Canada. Of the 1.2 million buildings in BC, more than 500,000 buildings[1] have a 10% in 50 years probability of being exposed to strong shaking (>MMI VII[i] or "very strong shaking") that can cause moderate structural and heavy non-structural damage. Earthquake-resistant buildings designed to withstand strong lateral forces will fare better than older buildings without seismic design elements, such as unreinforced masonry and non-ductile concrete. In addition, buildings with structural irregularities such as a soft storey[ii] will not perform as well during earthquake shaking. Structures built on water-saturated granular soils can liquefy and have their foundations give way, causing structures to collapse. Seismic waves can be amplified where sediment has accumulated in great thickness (sedimentary basins), dramatically increasing the shaking experienced by structures built in such areas. This is the case in parts of the Lower Mainland, where development built on the thick sedimentary deposits of the Fraser River delta are more vulnerable to ground shaking.

[i] *MMI is the Modified Mercali Intensity scale. "VII" on the scale represents "very strong shaking." The degree of structural damage is dependent on the design and construction of the structure.*

[ii] *"Soft-storeys" are multi-storey buildings with large openings such as windows, often on the lower floor. Such storeys and are weaker and more flexible than the storeys above.*

IMPACT ON INFRASTRUCTURE

Earthquake ground shaking and secondary effects can damage infrastructure, disrupt services, and cause secondary impacts. Examples include:

- Dams and other structures, such as dikes and retaining walls, may be vulnerable, putting people and assets at risk from floods or landslides.
- Vulnerable linear structures, such as older, brittle water and sewer pipes, can be damaged or outright broken.
- Weakened telecommunication systems can be overwhelmed even if they don't fail outright, jamming local and regional communications.
- Outfall from sewer lines that break can spill into sensitive ecological areas, and debris can overwhelm waste management systems.
- Damage to transportation corridors may limit access to damaged areas and inhibit response and recovery.
- Impacts to port infrastructure can cause major disruption to the transportation of goods and services along rail lines and highways that support a significant portion of Canada's imports and exports.

IMPACT ON PEOPLE

Damaged buildings can lead to loss of life, injury, and the displacement of large numbers of people from their homes as well as result in significant direct and indirect social, cultural, and economic losses within days, months, and years after a major earthquake. Vulnerable people will be further challenged to cope with and recover from a damaging earthquake. Vulnerable populations include children, seniors, and people with chronic mobility, sensory, or cognitive disabilities. People with low

INSIGHTS FROM 2011 CHRISTCHURCH EARTHQUAKE FOR BC

Figure 2: Demolishing of a building destryoed by the earthquake of 2011 in Christchurch, New Zealand (Photo: KiraVolkov/istock).

The impacts of the 2011 earthquake in Christchurch, New Zealand, can provide insights into what we could anticipate in some of the larger communities in BC, such as Victoria and Vancouver. In Christchurch, a city of nearly 400,000 people, roads and bridges were damaged, which hampered rescue efforts. Liquefaction and surface flooding were prevalent, and road surfaces were damaged by liquefaction. Cars and buses were crushed by falling debris. Damage occurred to many older buildings built before stringent earthquake codes were introduced. As of 2015, 1,240 buildings were demolished as a result of the damage inflicted by the 2011 quake (Figure 2). Following the quake, the downtown core remained cordoned off for three years, impacting economic activity and growth in the area.[4]

incomes are also more vulnerable and will have a harder time to recover. Individuals and communities who are disadvantaged and face social barriers (racism, classism, sexism, ableism, etc.) are likely to experience disproportionate impacts from disasters, including earthquakes.[2] These communities are more likely to live in seismically vulnerable buildings, have less access to government support, fewer resources, and less adaptive capacity to survive and recover from disruptions.[3]

IMPACT ON ECONOMY

In addition to direct losses, overall economic activity will be significantly impacted by a major earthquake due to interruption of utilities, services, and supply chains supporting the movement of goods and services locally, regionally, and nationally.

EARTHQUAKE THREAT AND PAST EVENTS

The top five damaging earthquakes that have impacted BC[5] include events in 1700, 1929, 1946, 1949, and 2001. They ranged in magnitude from 7.0 for the 1929 Haida Gwaii earthquake (at the time known as Queen Charlotte Islands) to M9.0 for the 1700 Cascadia megathrust earthquake. The M8.1 earthquake in 1949 in Haida Gwaii is the largest earthquake recorded by instruments in Canada.

Some of these events caused damage. First Nations oral histories indicate coastal communities lost many lives, structures, fishing boats, the destruction of a village near Pachena Bay, and more in the 1700 earthquake and tsunami. The earthquakes from the 1940s were reported in newspapers of the time: the 1946 earthquake damaged a school and other structures in Courtenay, knocked down 75% of the chimneys in the nearest community, triggered more than 300 landslides, and ultimately caused two deaths; the 1949 earthquake caused damage to communities on Haida Gwaii. An earthquake in 2001 was widely felt in southwestern BC but caused minor damage, such as broken windows, pipes, and chimney damage.

The relatively low frequency of damaging earthquakes in BC affects the perception of risk and leads to less opportunity for action (as such opportunity is usually created after an event). Most of BC's earthquakes have been in remote areas or in the distant past, making our society relatively complacent to earthquake risk, leading to inadequate funding and low political will to reduce the risk.

DRIVERS OF RISK

Physical and social vulnerabilities in society are the leading drivers of seismic risk in BC. An overwhelming majority of structures in the existing building stock were designed and constructed using building codes with low levels of seismic provision. Limited funding options to update infrastructure to a higher standard beyond saving lives, and the lack of lived earthquake experience among residents, contribute to this physical risk. For example, in Vancouver, over half of the city's 90,000 buildings were built prior to 1974 and have no or little seismic resistance, leaving residents and workers vulnerable to disruption, displacement, and injury or loss of life. In Vancouver, as in much of the province, this building vulnerability is the primary driver of seismic risk.

With an increasing population and expansion of the built environment in areas of high seismic hazard, seismic risk increases. High seismic hazard zones are areas in the province susceptible to ground failures, liquefaction (where the soil turns to quicksand and cannot support structures), increased shaking, and earthquake-induced landslides.

UNDERSTANDING RISK

WHAT SOURCES HELP US UNDERSTAND HAZARD AND RISK

A wide range of data and information types contributes to understanding earthquake threat and risk in BC. Below is an overview of available data and information on earthquake hazard and risk. There are also private consulting and insurance companies that routinely model earthquake risk.

REAL-TIME HAZARD DATA

Real-time seismic data can be used for warning systems at the regional level or site level. This is useful for better understanding earthquake hazards in an area and their use in building codes. Earthquakes are detected in real-time through an array of sensors and integrated into the Canadian National Seismograph Network. The British Columbia Smart Infrastructure Monitoring System (BC SMIS) collects information at or near critical infrastructure locations, such as public schools, government offices, fire halls, ambulance stations, and bridges. In the offshore regions, Oceans Network Canada records and detects ground motion.

HAZARD ASSESSMENT

Seismic hazard assessment defines the extent and severity of ground motions and likelihoods. A probabilistic assessment refers to analyses that consider all possible earthquakes that could affect a region over a period of time. The Canadian Seismic Hazard Model[6] is the authoritative source for federal information on earthquake hazard, generated by Natural Resources Canada and updated every five years, most recently in 2020. The assessment is considered by the National Building Code (NBC) for the seismic provisions in the code. Subsequently, provinces and territories use the NBC as the basis for building codes, such as the 2018 British Columbia Building Code.

Higher resolution studies, including local seismic sources and site conditions, can be used by communities to refine risk assessments that account for local geological conditions. Earthquake hazard scenarios developed by Natural Resources Canada have recently become publicly available.[7] Other fundamental hazard research is undertaken by federal scientists, academic institutions, and joint working groups (e.g., Cascadia Coastal Hazards Research Coordination Network[8]).

RISK ASSESSMENT

Earthquake risk assessments in the form of damage and loss estimations are an important source of risk information. Robust methods have been developed to quantitatively assess risks associated with earthquakes. Most earthquake loss estimations focus on physical damage to buildings and direct impacts such as injury, loss of life, displacement, and economic loss. Only a few communities have completed an earthquake risk assessment in Canada, including the District of North Vancouver,[9,10] University of British Columbia,[11] City of Victoria,[12] and City of Vancouver.[13]

A provincial earthquake risk assessment was jointly developed between Emergency Management BC and Natural Resources Canada, although this is not available publicly.

A new national earthquake risk model developed by Natural Resources Canada using OpenQuake[14] software provides results at the neighbourhood scale.[15] The new public-facing website and the publication of the national earthquake risk model will be released in the fall of 2022 and will make earthquake risk information more widely accessible across Canada. The national earthquake risk assessment is based on aggregate building information and will be updated regularly in alignment with the national earthquake hazard assessment.

ASSETS (EXPOSURE) DATASET

The National Human Settlement Layer[16] and the National Social Vulnerability[17] dataset provide geospatial details about people, buildings, and assets across Canada. As new models become publicly available, feedback and guidance from practitioners will guide how risk information can guide business owners, financial analysts, emergency managers, community planners, and the public to become more resilient to earthquakes.

POST-DISASTER DAMAGE ASSESSMENT AND DATA COLLECTION

BC Housing is tasked to carry out post-disaster rapid damage assessments of buildings. This has been conducted for other hazards, including wildfires and floods, but not tested for earthquakes due to the paucity of recent damaging earthquakes in BC. Private modelling companies and insurance and reinsurance companies compile post-event data. Public agencies also compile data and publish bulletins, such as Public Safety Canada's Canadian Disaster Database[18] or the international EM-DAT database.[19] The Canadian Association for Earthquake Engineering conducts reconnaissance after damaging earthquakes and publishes findings in a report to document lessons learned and their applicability to engineering practice in Canada.[iii]

OTHER RESEARCH PROJECTS AND DATASETS

Ongoing academic research within BC is conducted to develop tools that quantify and mitigate earthquake risk. Multiple open-source tools exist to assess the performance and functionality of buildings following an earthquake, including a tool (TREADS)[20] developed at the University of British Columbia. Other efforts at UBC include the development of Canada-specific fragility and vulnerability functions, which enhance the accuracy and reliability of seismic risk assessment results. This work builds upon the Disaster Risk Reduction (DRR) Pathways project (2019–2021) that focused on decreasing systemic risk through evidence-based disaster risk management, evaluating socioeconomic incentives for investing in disaster risk reduction, and the governing of risk information and risk management practice in BC.

GUIDELINES AND TOOLS FOR HAZARD AND RISK ASSESSMENTS

There are no guidelines or standard approaches defined for conducting quantitative earthquake hazard and risk assessments in Canada and BC. When conducting a risk assessment, ongoing community engagement is essential to provide an understanding of associated risks. It is essential that First Nations and Indigenous communities be included in all engagements.

Natural Resources Canada recently became a member of the Global Earthquake Model. This platform provides access to open-source tools that can assess earthquake hazards and risks.[21]

REDUCING RISK

Emergency Management BC developed the *BC Earthquake Immediate Response Plan*[22] in 2015, which is currently being updated. The plan lays out a shared and coordinated responsibility for sustained response and recovery. As of now, there is no provincial earthquake risk management strategy outlining priorities and requirements for earthquake risk reduction in the province. In 2018, BC became the first province to adopt the *Sendai Framework for Disaster Risk Reduction*, which encourages identifying and mitigating seismic risk. This, along with the ongoing Emergency Program Act Modernization in BC, provides an opportunity for implementing policies aiming to reduce earthquake risk in BC.

In BC, detailed earthquake mitigation plans can be found in the District of North Vancouver (*Earthquake Ready Action Plan*)[23] and in the City of Vancouver (*Earthquake Preparedness Strategy*[24] and *Resilient Vancouver Strategy*). Integrated Partnership of Regional Emergency Managers (IPREM) and Metro Vancouver have developed a disaster debris management plan[25] and regional temporary provision of drinking water guideline to support earthquake recovery.

PRACTICE AND CAPABILITIES

Managing physical risk from earthquakes is commonly approached by retrofitting existing buildings and developing building codes and standards for new buildings. It should be noted that financial losses from physical risk can never be fully eliminated and remaining losses should be managed by risk transfer mechanisms through insurance, reinsurance, and/or government funding. Social impacts of earthquakes are managed by building social capital through community networks, community resilience hubs, and community support programs—especially for marginalized and vulnerable groups.

SCHOOL SEISMIC UPGRADE PROGRAM AND GUIDELINES

A successful initiative in reducing existing earthquake risk is the provincial Seismic Mitigation Program (School Seismic Upgrade Program)[26] led by the Ministry of Education, working with Engineers and Geoscientists of BC with support from the University of British Columbia Civil Engineering Department. The program, started in 2004, aims to reduce the seismic risk of public schools through several mitigation

[iii] *In the US, EERI, GEER, STEER, EEFIT, and other organizations study earthquakes in the immediate aftermath, using funding made available through agencies like the National Science Foundation.*

measures, including retrofitting school buildings. Since launching the Seismic Mitigation Program, the Ministry has spent over $1.9 billion to complete high-risk seismic projects throughout the province. The program includes the development of seismic assessment tools and guidelines for the performance-based seismic retrofit of school buildings.[27]

EXISTING BUILDINGS RETROFIT PROGRAMS

Currently, the only program supporting retrofit of existing buildings is from the City of Victoria, which offers a Tax Incentive Program (TIP)[28] to eligible owners of heritage-designated commercial, industrial, and institutional buildings. Guidelines exist for those interested in voluntary retrofits to aid homeowners.[29,30]

BUILDING CODES

Building codes in Canada have evolved since the first National Building Code (NBC) was released in 1941. The seismic provisions are periodically updated to reflect new scientific knowledge. Risk tolerance levels have also evolved over time, from the first probabilistic ground motions with a 100-year return period (~40% chance of exceedance in 50 years) to the current 2,475-year return period (or 2% chance of exceedance in 50 years), reflecting a lower tolerance for risk of collapse in modern editions of the NBC. In Canada, the building code is developed at the national level, and each Province either adopts the code as is or modifies it, at which point the building code becomes law. One exception to this is in the City of Vancouver, which has its own unique bylaw.

High-importance buildings, such as schools and hospitals, are designed for higher loads and more stringent requirements. The BC Building Code, however, does not contain specific requirements for the seismic assessment of existing buildings, nor does it set minimum requirements beyond life safety. Safety design guidelines for critical structures, such as high- or extreme-consequence dams, are based on hazard intensities with less frequent but more severe earthquake events.

To develop these requirements, the Building Safety and Standards Branch has partnered with Natural Resources Canada and the National Research Council on a Seismic Retrofit Guidelines (SRG) Expansion Project. The SRG Expansion Project builds upon tools developed for the provincial school seismic upgrade program to develop new recommendations for the screening and retrofit of privately held buildings. These recommendations can be incorporated into future codes and regulations. A similar project[31] being completed by the National Research Council is a plan to assess the seismic safety of existing buildings.

SEISMIC VULNERABILITY OF DIKES

In a recent assessment of the vulnerability of dikes in BC to seismic hazards, more than 50% of the assessed dikes were found to have "very high" to "high" seismic risk, and 34% were at "high" to "moderate" risk of failure and subsequent flooding.[32]

Liquefaction is the most significant factor contributing to the vulnerability of dikes. In 2021, professional practice guidelines were developed by Engineers and Geoscientists BC to guide the seismic assessment and design of dikes in the province. The Ministry of Forests, Lands, Natural Resource Operations and Rural Development's *Seismic Design Guidelines for Dikes* (Second Edition) outlines technical requirements related to seismic assessment and seismic design of dikes under the *Dike Maintenance Act*. However, since then the Ministry has identified areas for improvement in how engineering professionals are applying the Ministry's guidelines and has requested that Engineers and Geoscientists BC develop practice guidelines to assist.[33]

GUIDELINES ON PERFORMANCE-BASED SEISMIC DESIGN OF BRIDGES

Professional practice guidelines in *Performance-Based Seismic Design of Bridges in BC* were developed in 2018 with the support of the BC Ministry of Transportation and Infrastructure, the Canadian Association of Earthquake Engineering, and the Structural Engineers Association of BC. These guidelines assist engineering professionals in carrying out the performance-based seismic design of bridges.[34]

MANAGING FINANCIAL RISK

Damages to physical assets lead to financial loss. Parties invested in physical assets are vulnerable to financial losses of varying levels. When an earthquake event happens in Canada, the losses will be borne by asset owners, such as personal or commercial entities, private and public infrastructure owners, developers, financial institutions, pension funds, and other collective investors. After a disaster, the Province may declare the event eligible for disaster financial assistance. Not every homeowner in BC knows, however, that earthquake damage is insurable and, therefore, not eligible for disaster financial assistance (DFA).[35] Disasters explicitly mentioned under the non-eligible section are wildfires, earthquakes, windstorms, snow load, sewer or sump-pit backup, and water entry from above the ground. To mitigate the risk of business disruption from a natural hazard event, businesses can purchase business disruption insurance.

Earthquake insurance provision in BC is much higher than elsewhere in Canada, with up to 70% uptake among residential properties.[36] This is a vast improvement over places like Quebec, where insurance rates remain around 3%–4% despite the appreciable risk.

By the end of the fiscal year 2022, the federal Office of the Superintendent of Financial Institutions and the British Columbia Financial Services Authority will require insurers to annually disclose earthquake exposures and meet a test of financial preparedness for the probability of a 500-year return period or 0.2% likelihood of occurrence in a given year.

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STRENGTHENING SOCIOECONOMIC RESILIENCE

Strengthening social vulnerability and community resilience means working together across a broad spectrum of people, but the co-benefits of such social programs and approaches have a greater effect on increasing resilience to other shocks and threats (like earthquakes) than investing in physical risk reduction measures alone. Social capital has proven to be the strongest and most robust predictor of population recovery following a catastrophe. For instance, following the devastating earthquake in Kobe, Japan, the city staff developed programs to create stronger solidarity among survivors, recognizing that rebuilding the social capital in a disaster zone is an essential component of recovery.[37]

INDIVIDUAL PREPAREDNESS

Individual protective actions, such as having an earthquake kit, securing furniture to the walls, and having a post-earthquake household emergency plan are important and achievable risk management strategies that many households can undertake to some degree. PreparedBC has created extensive materials[39] for the public to use to assist with preparedness planning and is actively engaged in outreach.

The Great British Columbia ShakeOut[40] organizes an annual earthquake drill every October to practice how to safely respond immediately to an earthquake using the drop, cover, hold technique and how to review or update emergency kits or plans. Many of the recommended individual protective measures may not be feasible for the most vulnerable community members, such as people with complex health conditions, disabilities, or who are living in poverty and may not have the financial or physical means to prepare for an earthquake appropriately. This is a gap that needs to be addressed.

Figure 3: Residents participate in an emergency preparedness exercise organized by the Dunbar Earthquake and Emergency Preparedness group as part of the Resilient Neighbourhoods Program Pilot, alongside images of a Needs and Offers board and volunteer roles and responsibilities (Photo: City of Vancouver).

CULTIVATING RESILIENT NEIGHBOURHOODS IN VANCOUVER

The City of Vancouver has established a Resilient Neighbourhoods Program to reframe and transform the way communities collectively prepare for emergencies while integrating efforts related to community connection, equity, climate action, and emergency preparedness. The program takes a capacity-building approach to build on services and networks that enable communities to thrive day-to-day and consider how these can be leveraged to address future hazards. The Resilient Neighbourhoods Toolkit[38] was co-created by the City and community partners and provides a guide for evaluating resilience, mapping assets, and creating neighbourhood resilience plans (Figure 3).

EARTHQUAKE EARLY WARNING

Earthquake early warning (EEW) is the rapid detection of earthquakes, real-time estimation of the shaking hazard, and notification of expected shaking. EEW provides seconds to tens of seconds of notice before strong shaking starts. This warning time can be used to perform actions that reduce injuries, deaths, and property losses.

Natural Resources Canada is developing a national EEW system (Figure 4) with federal, provincial, Indigenous and other partners and the United States Geological Survey. Alerts will be sent to the public through the National Public Alerting System. Tailored alerts will be sent to critical infrastructure operators and technical users, with the potential to trigger automated protective actions—such as opening doors, closing valves, sounding alarms, and diverting traffic. The national EEW network is focused on the west coast of BC and in the densely populated regions of eastern Ontario and southern Quebec. This national EEW system is slated to be operational in 2024.

Alert Ready is the public-facing brand name for the National Public Alert System. The program allows government officials to issue public safety alerts through mobile devices, television stations, and radio stations and can be activated during a large-scale disaster.[41]

Other existing monitoring and warning systems include: Oceans Network Canada's offshore seismic sensor network to monitor subduction activity along the west coast of Vancouver Island; UBC's EEW for private and public schools and other facilities, which it has operated since 2014; and EEW services provided by private companies to institutions like the Ministry of Transportation (e.g., to clear the Lower Mainland's Massey Tunnel) and the BC Legislature building in Victoria.

UBC has been conducting research on new and more advanced technologies, such as using a large density of sensors in urban areas, effective use of 5G networks, and adaptability of smart meters for use in a seismic network, to improve the reliability and efficiency of EEW.

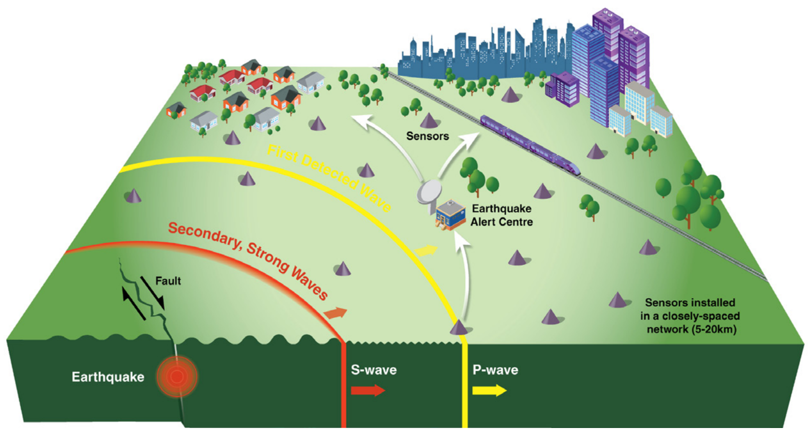

Figure 4: Natural Resources Canada is developing a national earthquake early warning system. Information on seismic P waves are collected before the damaging S waves to provide advance warning (Graphic: Natural Resources Canada).

ORGANIZATIONS INVOLVED IN EARTHQUAKE RISK MANAGEMENT

Organizations involved in earthquake risk management are summarized in Table 1.

GAPS IN REDUCING RISK

While considerable strides have been made to reduce earthquake risk in BC, gaps in practice remain, including:

1. **Community-level information, capacity, and resources** — Ideally, every community should have an earthquake risk profile with information about the threat levels of earthquake and secondary hazards and the vulnerability of critical infrastructure, buildings, and occupants to a damaging earthquake. Such information would help government and stakeholders, including the public, to understand: who and what are vulnerable to earthquakes; the likely impacts and consequences of a major earthquake; and how to design and target mitigation activities to reduce the risk and build resilience. However, very few communities have such information available for use in earthquake risk management.

   There is a severe lack of funds to quantify risk and address seismic risk mitigation. With the burden largely placed on property owners or municipalities, relatively few buildings have been retrofitted, even in cities exposed to potentially damaging earthquakes high, like Vancouver and Victoria. In smaller or rural towns with fewer resources, there may not be a person who specializes in seismic hazard and risk, let alone the opportunity to enact sweeping seismic risk mitigation programs. This is in part because governments and private citizens face myriad demands for their resources and seismic risk mitigation may not be the most urgent priority.

2. **Risk assessment** — A publicly available earthquake risk assessment for the Province does not exist. The publication of Natural Resources Canada's new national earthquake risk model in the fall of 2022 will help fill the gap. Some government agencies and communities have developed earthquake risk assessments for their specific infrastructure or location, but these assessments may not be publicly available or may be limited in scope. It is important to note that local assessments can provide more detailed and representative information than the national model; in such cases, those local details should be preserved to the extent possible.

3. **Buildings** — Building codes do not adequately address: 1) risk from aftershocks; 2) duration of shaking from subduction earthquakes; 3) seismic resilience of "housing and small buildings," although NBC includes a section on "Housing and Small Buildings," which provides prescriptive requirements that can be followed without the involvement of an engineer. There is a lack of local government enforcement of seismic provisions of the building code; most local governments leave it to engineers to self-check their seismic design.

   The largest gap in the building code is a lack of specificity on

Table 1: Organizations involved in earthquake risk management

Entity	Type of Organization	Legal Mandate and Role	Key Programs
Public Safety Canada	Federal government	Assesses capabilities and priorities of federal, provincial, territorial, and Indigenous partners for mitigation, preparedness and response to emergencies, and develops plans and preparedness strategies.	Federal Emergency Response Plan National risk profile (flood, earthquake, and wildfire) Requests for federal assistance Disaster Financial Assistance Arrangements Program Emergency exercises (tabletops)
Natural Resources Canada	Federal government	Provides authoritative geoscience knowledge for onshore and offshore lands.	Evaluation of regional earthquake hazard for the National Building Code National Earthquake Risk Profile Earthquake Early Warning System
Oceans Network Canada	Non-profit	Gathers real-time data for scientific research.	Earthquake Early Warning System
Emergency Management BC	Provincial government	Leads management of emergencies and disasters in BC and supports authorities within the Province's area of jurisdiction.	Emergency exercises and coordination during emergencies Provincial emergency plans and reports Indigenous Emergency Management Partnership Tables
BC Buildings Safety and Standards Branch	Provincial government	Sets standards and requirements for technical safety systems, equipment, and construction, renovation and alteration of buildings.	Seismic building codes
Technical Safety BC	Provincial government	Oversees safe installation and operation of technical systems and equipment across BC; independent, self-funded entity created under *Safety Authority Act* by the Province of BC.	Issues permits, licences and certificates for safe installation and operation of technical systems and equipment
Engineers and Geoscientists of BC	Professional association / non-profit	Regulates and governs BC's professional engineers and geoscientists under the authority of the *Engineers and Geoscientists Act*.	Professional practice guidelines

Entity	Type of Organization	Legal Mandate and Role	Key Programs
Integrated Partnership of Regional Emergency Managers (IPREM)	Regional government	Coordinates emergency management across Metro Vancouver; inter-governmental entity.	*Joint Municipal Regional Disaster Debris Management Operational Plan* Regional temporary provision of drinking water guideline
Local governments	Municipalities, regional districts	Provides services such as clean water, sewer systems, parks and recreation, and fire protection; implements climate action through the adoption of bylaws.	Emergency management plans Emergency operation centres Land-use plans Community resilience plans

standards for alterations to existing buildings. However, Engineers and Geoscientists BC has endorsed a number of technical guidelines for the seismic retrofitting of schools. Since 2011, three separate editions of the Seismic Retrofit Guidelines have been used for the seismic retrofitting of schools. A fourth edition for schools has been completed, along with guidelines for other types of low-rise buildings.

The largest gap in the building code is a lack of specificity on standards for alterations to existing buildings.

As part of the Existing Building Renewal Strategy, the Building Safety and Standards Branch (BSSB) in BC is exploring updates to the building regulatory system. Although current efforts are specific to seismic risk and the Seismic Retrofit Guidelines (SRG), legislative and regulatory considerations may relate more broadly to retrofits in existing buildings. The Province may adopt new SRG requirements as part of the BC Building Code or as a standalone regulation for existing buildings. The SRG is currently only for 43 building types—low-rise building construction types and heights common in schools. If it is to be used more broadly, it will need to be significantly expanded.

Developing Canada-specific building vulnerability functions has been challenging given the lack of observed damage data from past Canadian earthquakes. To create an inventory of vulnerable buildings and conduct risk assessments, more detailed information on buildings is needed to better understand these vulnerabilities.

4. **Infrastructure** — There is a need for post-disaster and recovery standards for critical infrastructure and financial support to invest in replacements and upgrades. Local governments have little to no budget to do this. Some infrastructure codes do not have adequate earthquake provisions. However, Infrastructure Canada's Disaster Mitigation and Adaptation Fund (DMAF) can be leveraged to support large-scale structural projects.

   More work is needed to understand the cascading impacts on critical infrastructure, such as how hospitals,[iv] telecommunications, and the flow of supplies will be impacted by the disruption of power and transportation. Scenario development with multi-sectoral participation can be an effective approach in

[iv] *Most BC hospitals run near capacity, and surge planning is often designed for a maximum of ~30 people (bus crash scenario).*

ADVANCING POLICY FOR SEISMIC RETROFIT IN THE CITY OF VANCOUVER

As part of its Earthquake Preparedness Strategy, the City of Vancouver partnered with Natural Resources Canada and local experts through the City's Seismic Policy Advisory Committee to begin work to develop a comprehensive risk assessment of its 90,000 privately held buildings. This assessment pulls together earthquake modelling results with urban and community planning efforts to generate a clear and actionable strategy to understand the city's seismic risk.

This initiative, developed through the City's first resilience strategy, connects seismic risk reduction in buildings into the City's larger resilient-building efforts. The ultimate goals of this ongoing work are to develop a sophisticated understanding of risk and risk reduction costs and benefits. It is an initiative that develops seismic risk reduction targets and generates policy options, which will be evaluated by City staff, partners in the community, industry, and all levels of government. From there it will be possible to decide together how best to act to reduce risk and advance resilience in buildings.

defining and understanding the interdependencies and impacts across CI systems, the vulnerability drivers, and developing risk management scenarios.

More work is needed to understand the cascading impacts on critical infrastructure, such as how hospitals, telecommunications, and the flow of supplies will be impacted by the disruption of power and transportation. Scenario development with multi-sectoral participation can be an effective approach in defining and understanding the interdependencies and impacts across CI systems.

5. **Response and recovery planning** — There is a lack of capacity and resources in emergency management teams at the local level to develop comprehensive response and recovery plans; existing planning is limited (most communities have at most one emergency planning coordinator responsible for entire emergency management programs).

   There is also a need for guidelines and suggested approaches in developing disaster recovery plans for all hazards, with specifics on post-earthquake recovery. FEMA's Pre-disaster Recovery Guide for Local Governments is an example of steps that can be taken by local governments and communities to support recovery following a disaster, with checklists, estimated timelinws for recovery steps and case study examples.[42]

6. **Earthquake science** — Given that few damaging quakes have been recorded in BC, there is a need to better understand where future earthquake sources are located, the frequency of ruptures, and how a fault can rupture, including the direction of rupture (propagation) and how the seismic wave travels through the ground or offshore. For offshore faults, there is a need to better understand rupture mechanisms to determine if a fault may induce damaging tsunami waves. At a given location, ground shaking can be intensified or dampened by the local site (geological and topographic characteristics), resulting in liquefaction and landslides. This knowledge of expected ground shaking is necessary to inform the design of infrastructure and buildings. High-resolution geoscience mapping both on land and offshore (marine and coastal regions) is required to determine if there are unknown active faults. This ongoing research is essential to build community resilience.

   In Canada, instruments have recorded earthquakes for the last 100 years, but modern digital data and a variety of new datasets (including GPS, precise seafloor imaging, and precise mapping using drones and satellites) are allowing for much more accurate earthquake hazard models. There is a need for ongoing paleoseismology studies to understand and assess the frequency of past earthquake events. The new earthquake early warning program will introduce new "strong motion" seismic instruments across BC to help advance knowledge of damaging earthquakes in the region.

7. **Managing financial impacts** — BC is doing well in terms of earthquake insurance uptake compared to other regions in Canada. However, gaps still exist for those who are uninsured, those who cannot afford their deductibles, or for managing a failure of the insurance sector. Despite high public awareness that BC is "earthquake country," there is a common misconception that federal or provincial funds will be available to those who are impacted by an earthquake. The Province of BC does not award financial assistance for insurable losses,[43] even if insurance is unaffordable to some. Therefore, earthquake damage is explicitly not eligible for recovery funds.[44]

OPPORTUNITY

RECOMMENDATIONS

The key recommendations for enhancing earthquake risk management in BC are listed in Table 2.

THE CHALLENGE

One of the biggest challenges that communities face is that information and mitigation plans are often focused on an individual hazard as opposed to looking at co-benefits from investments to address mitigation against the range of hazards. For example, retrofitting a building multiple times to mitigate vulnerabilities for each hazard individually could negatively impact resilience to other hazards (e.g., making the earthquake risk worse while retrofitting for flood) and is much costlier than doing the retrofits all at once in a coordinated matter. The first step to address this challenge is developing and providing communities with information on the range of hazards that a region can experience and providing case studies or examples of mitigation approaches that can be used to mitigate against a range of hazards.

Another significant challenge is for local governments to acquire appropriate resources for risk reduction efforts through provincial and federal grant programs—which, at the moment, are mostly focused on climate adaptation. The first step to address this challenge would be to provide information on the cost benefits of investing in mitigation to make communities and regions across BC more resilient to a range of hazards, including earthquakes.

Table 2: Recommendations

Recommendation	Impact	Priority Level	Capabilities Needed
Enable strategic and coordinated earthquake risk management			
1. Develop a provincial strategy and plan for a coordinated and holistic approach to reduce seismic risk in BC in alignment with the Sendai Framework.	Aligns components of earthquake risk management with different levels of governments; brings clarity on roles and responsibilities and long-term plans for reducing seismic risk in BC.	Critical	Legislation, technical, financial
2. Gather best practices and guidelines for key components of earthquake risk management at the local level.	Supports risk reduction and preparedness.	Necessary	Technical

Recommendation	Impact	Priority Level	Capabilities Needed
Advance understanding of earthquake risk, its drivers, and information sharing			
3. Gain a better understanding of interdependencies and cascading impacts of earthquakes on critical infrastructure through scenario planning.	Scenario planning brings different CI owners and providers together to discuss and understand interdependencies, cascading impacts, and capabilities for risk reduction.	Critical	Technical, financial
Effectively share data and information with users			
4. Access publicly funded risk assessment data and information from a central location.	Assists all levels of government in prioritizing hotspots and areas where mitigation will be most effective. Supports further research and analysis for advanced decisions and plans.	Critical	Technical, financial
5. Develop policy and mechanisms to share information about building hazard, risk levels, and risk reduction history at time of sale.	Better informs homeowners on how vulnerable their building may be in an earthquake.	Critical	Legislation
Use innovative communication methods and materials			
6. Bring awareness about earthquake risks and generate preparedness action by using innovative public education methodologies, including experiential methods.	Makes individuals more aware and better prepared for earthquakes.	Critical	Technical (including science of communication and human behaviour)
7. Use risk communication strategies that address known behavioural biases for earthquake risks.	Gives individuals an increased understanding of the risks associated with earthquakes and can evaluate costs and benefits of investing in risk reduction measures.	Necessary	Technical
8. Better communicate and educate stakeholders on structural vulnerability using non-technical formats.	Raises awareness and understanding for decision makers about vulnerable structures to prioritize mitigation.	Necessary	Technical
9. Provide communication briefs on earthquake hazards, including economic and public safety benefits of DRR, for politicians.	Make elected officials aware of earthquake risk and proactive measures to make communities more resilient.	Critical	Technical
Manage earthquake risk in new developments with research, policies, and programs			
10. Evolve building codes to provide design requirements to expand beyond life safety.	Increases societal resilience for faster recovery from a damaging earthquake.	Critical	Technical, legislation

Recommendation	Impact	Priority Level	Capabilities Needed
Manage earthquake risk in new developments with research, policies, and programs			
11. Address zoning and permitting in the Local Government Act to limit density of people and assets in areas exposed to damaging earthquake, flood, and landslide risks.	Limits density of people and assets in regions that are exposed to potentially damaging earthquakes, floods, and landslides.	Critical	Legislation
12. Expand the City of Vancouver's approach to engineered single-family buildings in areas exposed to potentially damaging earthquakes and increase the code for multi-family buildings.	Improves public safety and recovery rates in new buildings.	Critical	Legislation
Retrofit existing buildings with research, policies, and programs			
13. Conduct research to understand equity issues related to risk information and implementation of retrofitting programs.	Avoids accidental gentrification or inadvertent increase of risks for marginalized groups by driving up prices for safe homes.	Critical	Technical
14. Research and define design synergies between seismic retrofit, climate adaptation, and climate mitigation.	Helps buildings to withstand a changing climate and earthquakes.	Critical	Technical
15. Investigate means to apply standards to existing buildings and ensure compliance with building codes.	Helps buildings be more resilient to withstand and recover from damaging earthquakes.	Necessary	Legislation, technical, financial
16. Provide homeowners with seismic retrofit guidelines.	Informs homeowners on how to make their homes safe.	Necessary	Financial
17. Identify the locations and types of buildings most susceptible to structural damage.	Provides local authorities with information to inform structural mitigation strategies.	Critical	Technical
18. Expand existing Energy Step Code Program in BC to include seismic upgrades.	Empowers local authorities to implement and incentivize policies for energy efficiency and seismic resilience.	Recommended	Legislation
19. With financial institutions and provincial regulators, develop an incentive-based lending program based on proactive investments in mitigation and/or adaptation measures.	Provides incentives for individual property owners to invest in risk reduction measures and reduces financial liability of lending institutions.	Recommended	Financial

Recommendation	Impact	Priority Level	Capabilities Needed
Manage financial impacts			
20. With government oversight, incentivize earthquake property insurance that is risk-based and transparent (similar to the California and New Zealand insurance models).	Increase insurance uptake rates to support economic and financial recovery following an event.	Critical	Financial
21. Provide non-technical information for homeowners on the limitations of the Disaster Financial Assistance (DFA) Program for post-earthquake repairs.	Makes asset owners aware that DFA does not cover earthquake damages and they will need to purchase insurance for coverage.	Critical	Technical
Enhance post-disaster recovery planning and practices			
22. Establish neighbourhood resilience hubs across the province.	Creates social connection and a societal approach to all-hazard preparedness, mitigation, response, and recovery.	Recommended	Financial
23. Revise protocols for seismic upgrades and post-disaster refuge to allow occupants to shelter in place where the structural integrity of a building has been confirmed.	Minimizes socioeconomic disruption to individuals and businesses and accelerates post-disaster recovery.	Recommended	Financial
24. Streamline permitting and approval functions to replace and/or repair buildings damaged in an earthquake and prioritize structures critical to the recovery process.	Reduces the time to recover following a disaster event.	Necessary	Financial

RESOURCES

BC AND CANADA

1. An authoritative source of earthquake information that provides details on past earthquakes in Canada, seismic hazard values for all parts of Canada, seismograph viewers for stations, earthquake early warning, and general information on earthquakes.

Natural Resources Canada. "Earthquakes Canada." Accessed May 30, 2022. https://www.earthquakescanada.ca/.

2. The national association that proactively represents Canada's insurers. Two earthquake risk scenarios have been commissioned by the Insurance Bureau of Canada, to help inform earthquake insurance in Canada.

Insurance Bureau of Canada. "Earthquake Insurance." Accessed May 30, 2022. http://www.ibc.ca/ns/home/types-of-coverage/optional-coverage/earthquake-insurance/.

3. A collaborative project that provides and develops maps that depict shaking amplification due to local geological site conditions, liquefaction, and landslide susceptibility for communities of the Lower Mainland.

Institute for Catastrophic Loss Reduction, University of Western Ontario, and Emergency Management British Columbia. "Metro Vancouver Seismic Microzonation Project." Accessed May 30, 2022. https://metrovanmicromap.ca/.

4. An operations plan for Metro Vancouver on disaster debris management for debris generated during an earthquake in the Lower Mainland.

Integrated Partnership for Regional Emergency Managers. *Joint Municipal Regional Disaster Debris Management Operational Plan For Metro Vancouver region and members*. October 2017. http://www.metrovancouver.org/services/emergency-preparedness/Documents/2017JMRDDMPlan.pdf.

5. A best-practice example of a plain language report that provides insights on the possible consequences a damaging earthquake in the District of North Vancouver.

District of North Vancouver. *When the Ground Shakes*. North Vancouver: District of North Vancouver. Accessed May 30, 2022. https://www.dnv.org/sites/default/files/edocs/when-the-ground-shakes.pdf.

6. News reporter and CBC host provides insights from scientists, engineers, and emergency planners about earthquakes, disaster response, and resilience from BC and beyond. The book includes firsthand accounts from people who have survived deadly earthquakes, explains the science, and asks what we can do now to prepare ourselves.

Craigie, Gregor. *On Borrowed Time*. Fredericton: Goose Lane Editions, 2021.

INTERNATIONAL

7. Intended for homeowners in California, this site provides knowledge on seismic ordinances, assessments, and retrofit requirements for cities across California.

Seismic Ordinances. "Seismic Ordinances of California." Accessed May 30, 2022. https://www.seismicordinances.com/.

8. A non-profit organization that provides affordable earthquake insurance policies for Californian homeowners. The policy includes discounted premiums for homeowners that retrofit their homes.

California Earthquake Authority. "Prepare your house for an earthquake." Accessed May 30, 2022. https://www.earthquakeauthority.com/Prepare-Your-House-Earthquake-Risk.

9. An authoritative source of earthquake risk information for funding opportunities, hazard maps, building codes and standards, publications, training, and earthquake insurance for the United States.

Federal Emergency Management Agency. "Earthquake Risk." Accessed May 30, 2022. https://www.fema.gov/emergency-managers/risk-management/earthquake.

10. NDC, along with experts in the fields of construction, finance, and economics, estimated retrofit costs, researched best practices in peer cities, examined economic impacts of retrofits, and studied a comprehensive set of potential funding sources.

National Development Council. "Funding URM Retrofits: Report to City of Seattle from National Development Council." May 2019. https://www.seattle.gov/Documents/Departments/SDCI/Codes/ChangesToCodes/UnreinforcedMasonry/FundingURMRetrofitsSummary.pdf.

11. A guide for local US governments to develop seismic retrofit incentive programs. The guide includes case studies of US cities that have promoted and implemented earthquake retrofitting, information on the use of zoning as an incentive to retrofit, local government finance options, and a description of the Unreinforced Masonry Buildings (URM) law.

Federal Emergency Management Agency. *FEMA 254, Seismic Retrofit Incentive Programs: A Handbook for Local Governments*. 1994.

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