

THE CASE FOR AN ADVANCED NATIONAL EARTHQUAKE MONITORING SYSTEM FOR CANADA'S CITIES AT RISK

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ABSTRACT

More than half of Canadians live in areas prone to earthquakes, and over 75% of Canada's population lives in urban areas, thus concentrating most of Canada's vulnerability to earthquakes. The earthquake threat is both to the safety of Canadians and to the economic health of the nation, because the federal government, by prior agreement with the provinces, is the prime financial responder to major natural disasters. Recent advances in seismic and GPS sensor technology, digital communications, and computer hardware and software make it possible to revolutionize our approach to seismic hazard mitigation in urban areas. The Canadian Urban Seismology Proposal (CUSP) would mitigate the impacts of earthquakes in Canada by deploying a real-time earthquake monitoring system focussed on Canada's population centres at risk.

Introduction

Although the future occurrence of earthquakes is inevitable, catastrophic losses are not. Proper mitigation practices and informed emergency response procedures can greatly reduce the impact. The implementation of effective mitigation practices involves long and complex processes. These processes require four steps: (1) quantitative assessment of the hazard and its consequences; (2) development of proper building designs, practices, and codes; (3) effective land-use planning; and (4) acceptance and implementation of mitigation practices. Recent advances make it possible to revolutionize the approach to seismic hazard mitigation in urban areas and thus contribute to all four steps. It is vital for Canada's long-term economic security to convert an evident hazard to a risk that can be understood in terms of health and safety and fiscal loss, in order to achieve a tolerable trade-off between mitigation activities and the consequences of large earthquakes. Ever increasing infrastructure and population results in a greater exposure to seismic risk. Earthquake monitoring provides the foundation for the development of systems which can reduce this risk.

Current Situation in Canada

Earthquake History

In the past century large (magnitude 6 or larger) earthquakes have occurred at a frequency of almost once per year within or near the boundaries of Canada. While the majority of these have

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been in sparsely populated regions, at least ten events caused significant damage (Table 1), and in a few cases, loss of life. Parts of eight provinces and all three northern territories are exposed to earthquake hazard (Fig. 1). More than half of Canada's population lives in the part of the country most endangered by earthquake hazard. Five of Canada's largest cities (Vancouver, Montreal, Ottawa-Gatineau, Victoria, Quebec City) lie in these regions of significant seismic hazard (Fig. 2).

Earthquake Monitoring

Currently, almost all earthquake monitoring and most of the associated hazard research in Canada is undertaken by the Geological Survey of Canada (GSC). The Canadian National Seismograph Network provides the backbone of the earthquake monitoring program. It consists of a core network of twenty-four 3-component broadband seismograph stations across the country supplemented by regional networks in more populated, earthquake-prone areas. Data are transmitted via satellite to both the Ottawa and Sidney (near Victoria, B.C.) offices in real time for automatic processing and analysis. The dual processing centres ensure the required high reliability of the program. In addition, a number of strong motion seismographs are located in urban regions to provide on-scale recordings of strong ground motion during large earthquakes. A mix of modern digital and aging smoked paper portable instruments are available for rapid deployment to record aftershocks.

The regional networks help to provide denser seismograph coverage in earthquake-prone areas with large populations and/or industrial infrastructure. This lowers the national magnitude detection and location threshold from about magnitude 3.5 to 2.5, and permits more accurate earthquake locations for better hazard estimates. Regional networks contain some broadband and 3-component short-period seismographs, but are mainly just short-period vertical instruments. The regional networks rely heavily on external partners who provide seismograph sites or communications infrastructure.

The present GSC strong motion instrumentation consists of about 50 stand-alone, self-triggered strong-motion seismographs, half of which are antiquated photographic film recording instruments (Rogers et al., 1999). The urban network is extremely sparse, with less than half of the strong-motion seismographs deployed within urban areas, primarily in Vancouver and Victoria. There is just one strong motion instrument in each of Ottawa, Montreal, and Quebec City, and none in Toronto. None of the digital instruments have communication capability and so must be visited after an earthquake to recover their data. By modern standards the current network is inefficient, ineffective for many purposes, and expensive to maintain.

Global Positioning System geodetic monitoring is being applied in earthquake prone regions worldwide. The GSC has deployed a network of 8 continuous-recording GPS instruments in British Columbia, which has successfully demonstrated that strain is accumulating for a huge earthquake on the west coast subduction zone and revealed aseismic slip events that might trigger them (Dragert et al., 2001).

Roles and Responsibilities

Canada's current national seismic network was designed for maximum sensitivity to small

earthquakes, in order to generate a catalogue of national earthquakes. It is currently used to provide timely information after felt or damaging earthquakes (for emergency response and the media), better understanding of earthquake occurrence, volcanic eruptions and tsunamis, as well as warning that an offshore earthquake may have generated a tsunami, or that a volcanic eruption may be imminent. For providing greatly enhanced safety at relatively low cost, the network supplies the basic data needed to assess the likely level and character of ground shaking from future earthquakes, and thus input for setting guidelines in building codes for earthquake-resistant design and construction.

Seismic Hazard Assessment

Canadian seismic hazard maps have been successively refined as new information from significant earthquakes has been assessed. Three generations of seismic hazard maps have been produced at roughly 15-year intervals (1953, 1970, 1985; see Fig. 2), and a fourth generation is now justified (Basham, 1995). The GSC initially released a suite of new seismic hazard maps for trial use in 1995. These “4th Generation” maps were revised in 1999 and will be the basis for seismic design provisions in the 2003 edition of the National Building Code of Canada (Adams et al., 1999). The new maps incorporate a significant increment of earthquake data (including revisions to older earthquake locations and magnitudes) and recent research on source zones and earthquake occurrence, together with recently-published research on strong ground motion relations. These allow computation of spectral acceleration values for the range of periods important for common engineered structures, as well as the peak ground acceleration parameter from the current (1985) maps. The earlier publications on the 4th generation maps provided 10%/50 year values directly comparable to the 1985 maps, but the future code will be based on 2%/50 year (0.000404 per annum) values, as these design ground motions are considered to provide a more uniform margin against collapse across the country (Adams et al., 2000).

Benefits of Seismic Hazard Research

The economic value of earthquake-related activities is the benefit from the reduction in loss from a disastrous earthquake less the cost of complying with the earthquake provisions of building regulations. Swan (2000) starts with the best loss estimation yet made for Canada - Munich Reinsurance's (1992) assessment of a mean loss of \$12 billion to buildings and contents in Greater Vancouver from a magnitude 6.5 earthquake on the Canada-U.S. border, 30 km south of Vancouver's downtown core. U.S. engineers have estimated the difference in construction standards between California and moderate-seismicity states where seismic codes are less stringent. They estimate that a given earthquake shaking would cause 30% (for wood frame buildings) to 90% (for other structures) greater damage than in California (Rojahn, 1989). Canada's earthquake code is approximately proportional to California's, so avoidance of this extra damage is taken to be the benefit from earthquake-related studies (knowledge of earthquakes, estimation of earthquake shaking, and getting the results into the building code). The reduction is \$6 billion for the \$12 billion 1-in-500-year earthquake scenario, or \$12 million per year. Swan further estimates additional loss reductions of \$10 million per year from smaller (less damaging, more frequent) and \$9 million/year from larger (more damaging, less frequent) scenario earthquakes, for a total of \$32 million per year. Allowing for reduced fire damage and deaths and injuries associated with these earthquakes increases the savings to \$47 million. Earthquake code compliance costs for Greater Vancouver are estimated at \$680 million, and the corrected interest and depreciation on that sum is the annual cost of compliance, \$38 million. The net annual benefit is \$9 million for Vancouver. This was increased by a factor of 5 (since

Greater Vancouver comprised about one fifth of the total Canadian seismic risk according to Adams, 1989), for a net annualized saving of \$43 million. Canada currently spends about \$2.5 million per year on earthquake studies. Thus an average Canadian citizen (say in Manitoba) pays 8 cents for the national earthquake program through taxes each year, but receives \$1.45 in time-averaged annual benefits. This benefit accrues to all Canadians, even if they do not live in an earthquake zone, because by prior arrangement damage in any Canadian urban centre would be paid for largely from federal taxes collected nationwide.

Seismic Risk across Canada

A full assessment of seismic risk in Canada involves much non-seismological data, knowledge and skills to translate the effects of seismic hazard shaking into likely losses. It is thus beyond the scope of this paper, and beyond the current mandate of the GSC. However, a first approximation is extremely useful for allocating resources to those places where the benefits will be largest. Our method follows from our unpublished work and from Adams (1989), and assesses the distribution of urban seismic risk in Canada from the sum of city population times the probability of damaging ground motion, as set out in Table 2. For the probability, we used the more-likely of two damage thresholds to capture the different hazard to short (1-2 storey) and tall (circa 10 storey) buildings, and to eastern and western Canada. Choosing different thresholds or ground motion parameters would produce results that differ in detail, but substantially mimic the risk distribution shown in Fig. 3. Between them, the greater Vancouver and Montreal account for more than half of the urban seismic risk. Canada's six largest cities at risk account for over three-quarters of the risk.

The Canadian Urban Seismology Proposal (CUSP)

Like Canada, many countries are upgrading their national earthquake monitoring networks to take advantage of the cost savings and efficiencies and the improved capabilities of modern technology. For a modern, balanced program we propose: a greatly-expanded network of urban strong-motion seismographs; new seismographs to provide effective monitoring around urban areas; two portable seismograph networks to facilitate the studies of earthquake effects and local variations in ground shaking; approximately 30 new GPS stations allow accurate measurement of local strain rates around the urban areas of southwest British Columbia and eastern Canada; and augmented data acquisition, archiving, and distribution facilities to manage the expanded client base for information services (NEHP, 2001).

The greatest need is, however, for strong-motion seismograph networks in urban areas - the existing ones are inadequate to meet the needs of emergency management, engineering and research communities. At least 1000 new instruments are necessary for an effective national system. The number of instruments is a cost-effective balance. It is determined by deploying a sufficient density of instruments in the highest risk urban regions to characterize the strong seismic shaking hazard throughout the region, on all types of ground used for construction. In urban regions with a lower hazard, only representative ground sites will be instrumented, but with an overall instrument density sufficient to characterize ground motion for emergency response. A risk-benefit analysis suggests the instruments be deployed considering the degree of urban vulnerability, as indicated in the final column of Table 2. More than 3/4 of these instruments will be deployed in and around Canada's five most vulnerable cities: Vancouver, Montreal, Victoria, Quebec City and Ottawa/Gatineau. A depiction of real-time sensor density, both current and proposed, is given in Fig. 4. In addition to the named urban

areas, prudence requires some instrumentation in many smaller centres at risk as well a few sensors in larger centres currently thought to be at low risk.

The next, “5th Generation” of seismic hazard maps must incorporate the new understanding and unexpected lessons that will come from the next decade’s earthquakes. It will be critical that we have the best possible recording network of seismographs and strong motion instruments in place to record, in particular, the next large ($M > 6$) earthquakes in each of southeastern and southwestern Canada, because they will provide the critical data to decide between the current models for ground motion. We also expect that seismic hazard for major cities will be computed differently (while retaining a Cornell-McGuire approach for the nation as a whole). The shaking to be expected from damaging earthquakes, say magnitude 6 to 7 can be simulated from records of moderate earthquakes, say magnitude 4 to 5. These ground motion records could then be used directly in design, thus avoiding the uncertain assumptions necessary when strong ground motion relations must be used. However, to apply the method we need to have in hand the records of the moderate earthquakes (which are not an annual occurrence near urban areas). Therefore it is essential that we act soon to deploy many weak and strong motion recorders in major Canadian cities.

A vision for 2006

With an advanced earthquake monitoring system the National Earthquake Hazards Program could provide four important new services. Clients for these services include emergency response organizations (federal, provincial, municipal), transportation organizations (railways, highways), energy producers and distributors (pipelines, utility companies), and critical industrial operations such as nuclear power plants, dams, and liquefied natural gas plants.

Immediate, accurate and detailed shaking maps following an earthquake

Shaking maps available 24 hours a day, 365 days a year will aid in directing emergency response and recovery and provide critical data to analyze structural failures. Figure 5 illustrates a hypothetical future product to be generated.

Detailed maps of hazard levels within cities

Weak motion records from many small earthquakes at many sites can identify hazardous areas, and provide ground-truth to direct remote sensing and geological studies. Detailed maps will focus on understanding localized variation in shaking for effective urban planning and appropriate mitigation of earthquake effects.

Maps of crustal deformation and its rate

Detailed deformation monitoring can determine contemporary strain accumulation and the level of hazard that threatens urban areas.

Rapid communication of approaching ground motion

Dense seismic networks make it possible to provide early warning of approaching seismic waves to automatically close key switches and valves to ensure safe shutdown of vulnerable facilities.

December 2001 Status and Prognosis

The CUSP proposal has received initial funding as a two-year pilot project. This will see existing strong motion instruments replaced with modern instruments having full communications capability and the deployment of a trial, densely-spaced urban strong ground motion network in a

section of Greater Vancouver. If the proposal is fully implemented, accurate shaking maps for entire cities would become available minutes after potentially damaging earthquakes, so as to quickly assess damage and deploy emergency resources. Intense earthquake shaking can vary by a factor of 10 between suburbs of the same city, so records of small to moderate earthquakes before a major earthquake would be used to delineate areas where unusually strong shaking might be expected. In these areas, good practice would recommend that existing buildings be strengthened or land-use be regulated. Future codes for new buildings should also be improved to reflect the new understanding.

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* Publications indicated by * are available from www.EarthquakesCanada.ca

Table 1. Large or damaging earthquakes in Canada since 1900

DATE	LOCATION	MAGNITUDE
2001 02 28	Puget Sound	6.8 damage, deaths in U.S.A.
1992 04 06	Offshore British Columbia	6.8
1988 11 25	Saguenay, Que.	6.0 damage
1985 12 23	Nahami, N.W.T.	6.9
1982 01 09	Miramichi, N.B.	5.7
1980 12 17	Offshore British Columbia	6.8
1979 02 28	Yukon - Alaska border	7.5
1976 12 20	Offshore British Columbia	6.8
1970 06 24	Queen Charlotte Islands, B.C.	7.4
1965 04 29	Northern Washington state	6.5 damage, deaths in U.S.A.
1958 07 09	Yukon - Alaska border	7.9
1949 08 22	Queen Charlotte Islands, B.C.	8.1 damage
1949 04 13	Northern Washington state	7.1 damage, deaths in U.S.A.
1946 06 23	Courtenay, B.C.	7.3 damage, deaths
1944 09 05	Cornwall, Ont.	5.6 damage
1935 11 01	Timiskiming, Que.	6.2 damage
1933 11 20	Baffin Bay, N.W.T.	7.3
1929 11 18	Offshore Newfoundland	7.2 tsunami, deaths
1929 05 26	Offshore British Columbia	7.0
1925 03 01	Charlevoix, Que.	6.6 damage
1918 12 06	Vancouver Island, B.C.	7.0 damage
1918 02 04	Revelstoke, B.C.	6.0 damage
1909 01 11	Gulf Islands, B.C.	6.0 damage
1904 03 21	Passamaquoddy, N.B.	5.9

Notes: Earthquakes within 200 km of major Canadian cities are in **bold**. This list includes all the largest earthquakes since 1900 in, or very near to Canadian territory (those of magnitude 6.7 and larger), and some smaller damaging, or potentially damaging earthquakes near urban areas in Canada. These earthquakes produced shaking of Modified Mercalli Intensity VII or greater, which represents very strong shaking; the level of shaking at which structural damage begins to occur in well-built, ordinary buildings.

Table 2. Relative Seismic Risk for Canadian Cities

Urban Area	Population	Annual Probability	Vulnerability Index	Number of Instruments
Vancouver	1912000	0.00950	18175	300
Montreal	3326510	0.00350	11483	220
Ottawa/Gatineau	1010498	0.00320	3278	65
Victoria	317000	0.00930	2946	60
Toronto	4263757	0.00063	2690	50
Nanaimo	220000	0.00940	2077	40
Quebec	671889	0.00260	1776	35
Abbotsford	142000	0.00890	1260	25
Hamilton/Burlington/Brantford	709124	0.00110	767	15
St. Catharines/Niagara Falls	372406	0.00140	509	10
Edmonton	862597	0.00041	354	7
Calgary	821628	0.00041	335	7
Other cities	4309589	-	3027	60
Rest of Canada	10733000	-	-	100

Notes

1. Population as defined by Statistics Canada in the 1996 census, “urban areas” include named cities plus adjacent communities. The total urban population considered is 18.9 million out of the Canadian population of 29.7 million.
2. The annual probability of damage, given to 2 significant figures, is defined here as the more probable of the peak ground velocity or the peak ground acceleration corresponding to Modified Mercalli Intensity VII.
3. The suggested distribution of about 1000 instruments is made chiefly on the basis of urban vulnerability, which is estimated simply by multiplying the population by the probability of damage. The sum of vulnerability for the urban population considered is 48677. In addition to the named urban areas and other cities, 100 instruments are assigned to other towns at risk. Actual distribution of instruments would depend on many other factors, including a more sophisticated definition of vulnerability, the assessed benefits of monitoring smaller towns versus concentrated monitoring of the largest cities, local geology, distribution of urban development, and recommendations of local partners.

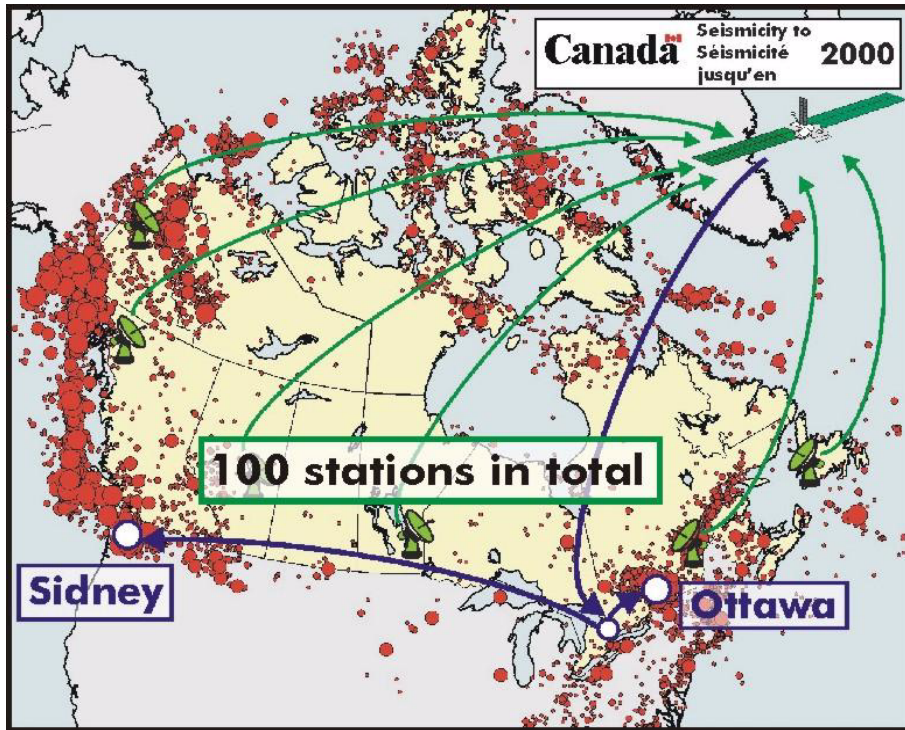


Figure 1. Canadian seismicity to 2000 and cartoon of Canadian seismograph network showing communication links and processing and analysis centres.

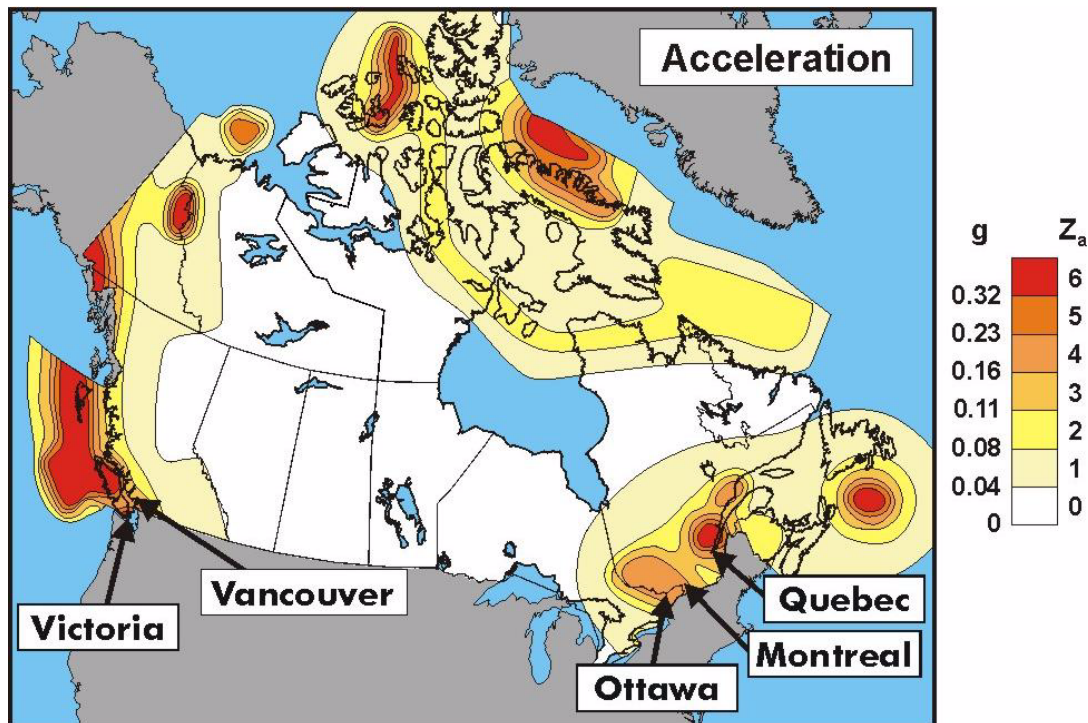


Figure 2. Current (1985) seismic hazard map of Canada, showing current level of expected ground motion at a probability of 10%/50 years. Five of Canada's major cities are in regions of increased seismic hazard.

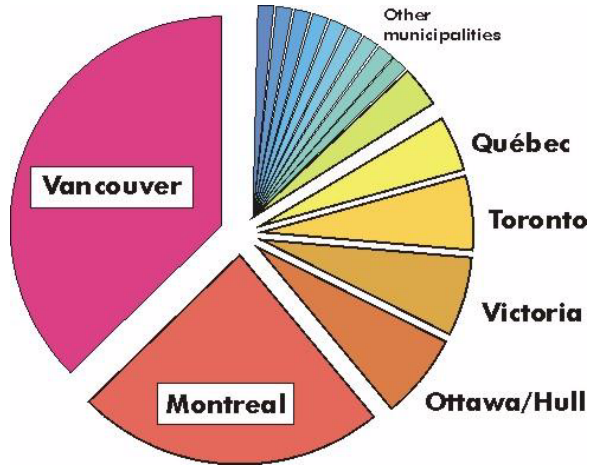


Figure 3. Relative distribution urban seismic risk in Canada (see Table 2). More than three quarters of the vulnerability is concentrated in six of Canada's largest urban areas.

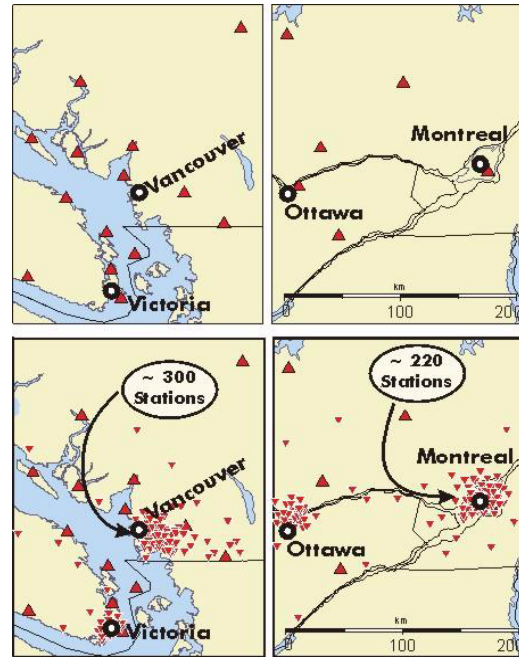


Figure 4. Cartoon of the current (top) and proposed distribution of real-time sensors.



Figure 5. Hypothetical product to be generated. Damage levels are computed from direct shaking measurements from the urban strong motion network, combined with known soil amplification and infrastructure distribution.