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New opportunities for Canadian earthquake monitoring, information, and research

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Abstract: Rapid advances in technology and decreasing costs of data collection and transmission are providing a wealth of new opportunities in earthquake monitoring, information, and hazard research. This paper outlines both the current situation and future directions of Natural Resources Canada in terms of earthquake monitoring and information dissemination in Canada. In addition, it describes some of the new research opportunities and products that would result from the deployment of modern, dense seismograph networks in urban areas such as greater Vancouver. These products, including 'ShakeMap', provide detailed, earthquake ground-shaking maps across urban areas. They assist with rapid emergency response efforts after a major earthquake, and with earthquake research, planning, and damage mitigation efforts before an earthquake.

Résumé : Des progrès technologiques rapides et les coûts à la baisse de la collecte et de la transmission des données offrent une multitude de nouvelles occasions dans les domaines de la surveillance des tremblements de terre, de l'information et de la recherche sur le risque séismique. Cet article présente un exposé de la situation actuelle à Ressources naturelles Canada en matière de surveillance des tremblements de terre et de diffusion de l'information qui s'y rattache et donne un aperçu des orientations futures. Il y est aussi fait mention de nouvelles occasions de recherche et des nouveaux produits que permettrait d'obtenir le déploiement de denses réseaux de séismographes perfectionnés dans des régions urbaines comme le Vancouver métropolitain. Des produits comme la « ShakeMap » (carte de secousse) permettent de représenter de manière détaillée les vibrations du sol engendrées par les séismes à l'échelle d'une région urbaine. Ces produits facilitent de rapides interventions d'urgence suite à des séismes importants, ainsi que la recherche sur les tremblements de terre, la planification et la mise au point de mesures d'atténuation des dommages avant que ne survienne un séisme.

INTRODUCTION

Earthquakes pose a threat both to the safety of Canadians and to the economic health of the nation. The federal government, by prior agreement with the provinces, is the prime financial responder to natural disasters. The first line of defence against earthquakes is provided by the seismic hazard maps in the National Building Code of Canada. Natural Resources Canada (NRCan) updates these maps based on earthquake recording and earthquake-process research. The ability to monitor earthquakes and shaking levels, and to rapidly provide this information to key clients, is evolving quickly due to rapid advances in technology and decreasing communication costs. The purpose of this paper is to provide a brief earthquake history of Canada, and to document the current situation and describe future possibilities in terms of earthquake monitoring, information, and research capability.

EARTHQUAKE HISTORY

During 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. Although the majority of these have been in sparsely populated regions, at least ten events caused significant damage and, in a few cases, loss of life. Some of the larger and more damaging earthquakes are listed in Table 1. 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, Montréal, Ottawa-Gatineau, Victoria, Québec) lie in these regions of significant seismic hazard (Fig. 2).

CURRENT SITUATION

Earthquake monitoring

The Geological Survey of Canada (GSC) operates the 'Canadian National Seismograph Network' (CNSN), a network of about 120 continuous-recording ('weak-motion') seismographs across Canada. More than 25 of these instruments are located on bedrock sites across southwestern British Columbia (Fig. 3).

Due to high seismic-noise levels in cities, none of these 'weak-motion' instruments are located in urban areas. For example, the closest continuous-recording seismograph to downtown Vancouver is on Bowen Island, more than 15 km away. Data from the CNSN are transmitted to offices in Sidney (British Columbia) and Ottawa (Ontario) by satellite, radio signal, microwave, telephone line, and the Internet. These data are received within a few seconds of real time. The

Table 1. Some large or damaging earthquakes in or near Canada since 1900.

DATE	LOCATION	MAGNITUDE
Feb. 28, 2001	**Puget Sound**	**6.8 damage, deaths in U.S.A.**
April 6, 1992	Offshore British Columbia	6.8
Nov. 25, 1988	**Saguenay, Quebec**	**6.0 damage**
Dec. 23, 1985	Nahanni, Northwest Territories	6.9
Jan. 9, 1982	**Miramichi, New Brunswick**	**5.7**
Dec. 17, 1980	Offshore British Columbia	6.8
Feb. 28, 1979	Yukon - Alaska border	7.5
Dec. 20, 1976	Offshore British Columbia	6.8
June 24, 1970	Queen Charlotte Islands, British Columbia	7.4
April 29, 1965	**Northern Washington state**	**6.5 damage, deaths in U.S.A.**
July 9, 1958	Yukon - Alaska border	7.9
Aug. 22, 1949	Queen Charlotte Islands, British Columbia	8.1 damage
April 13, 1949	**Northern Washington state**	**7.1 damage, deaths in U.S.A.**
June 23, 1946	**Courtenay, British Columbia**	**7.3 damage, deaths**
Sept. 5, 1944	**Cornwall, Ontario**	**5.6 damage**
Nov. 1, 1935	Timiskiming, Quebec	6.2 damage
Nov. 20, 1933	Baffin Bay, Northwest Territories	7.3
Nov. 18, 1929	Offshore Newfoundland	7.2 tsunami, deaths
May 26, 1929	Offshore British Columbia	7.0
March 1, 1925	**Charlevoix, Quebec**	**6.6 damage**
Dec. 6, 1918	**Vancouver Island, British Columbia**	**7.0 damage**
Feb. 4, 1918	Revelstoke, British Columbia	6.0 damage
Jan. 11, 1909	**Gulf Islands, British Columbia**	**6.0 damage**
March 21, 1904	**Passamaquoddy, New Brunswick**	**5.9**

Notes: Earthquakes within 200 km of major Canadian cities are in **bold.** This list includes all the largest earthquakes (those of magnitude 6.7 and larger) since 1900 in, or very near to, Canadian territory, 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.

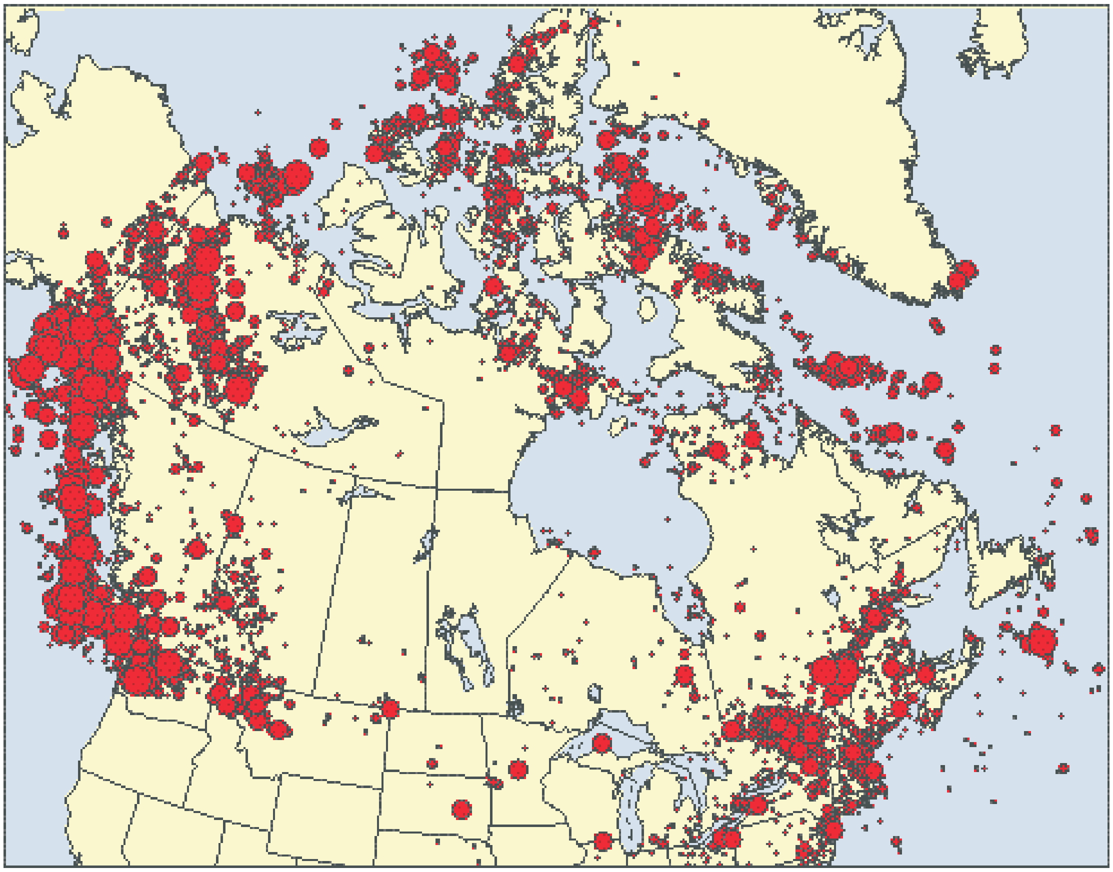


Figure 1. *Canadian seismicity to 2000. The largest dots are earthquakes of magnitude 7.5 to 8.2, the smallest dots are magnitude 4.5.*

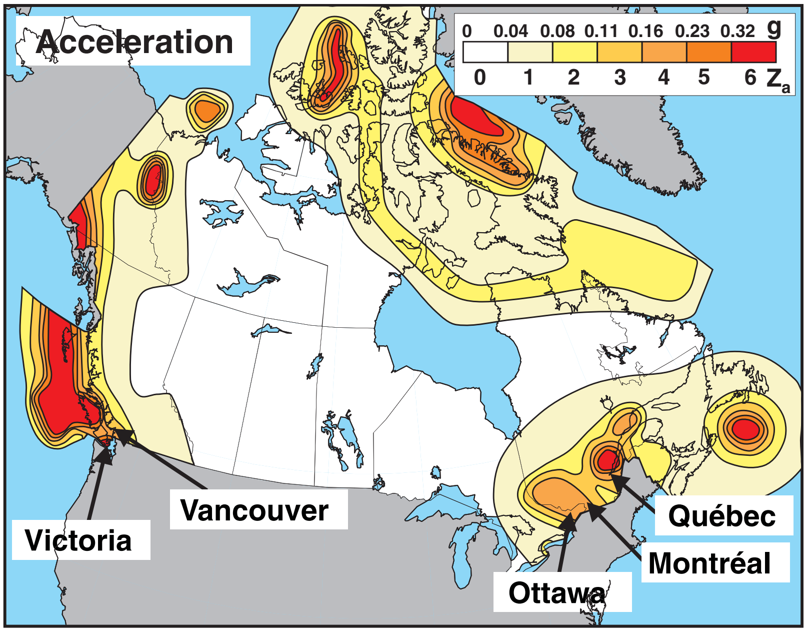


Figure 2.

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

CNSN records more than 300 earthquakes each year across southwestern British Columbia (nearly one per day), and more than 2000 earthquakes across Canada each year.

The GSC also operates a network of about 50 accelerographs across Canada. These instruments are designed to record strong ground shaking for engineering-design purposes. These instruments only trigger when ground motion above a defined threshold is detected (typically once every few years). These instruments have no communication capability and must therefore be visited after an earthquake for recovery of data. Only about half of these instruments are digital; the remainder record on photographic film.

Earthquake reporting

Earthquake information is provided around the clock, with an earthquake seismologist on call 24 hours a day, 7 days a week. Data from seismographs across Canada are continuously monitored by computers. If a 'seismic event' is detected, it is automatically located and a preliminary location and magnitude provided to Canadian seismologists within about 5 to 7 minutes. For large (magnitude greater than 5) earthquakes, these automatic solutions are sent directly to clients such as CN Rail, Hydro Quebec, and Hydro Ontario. When a felt or potentially damaging earthquake occurs, in addition to locating and determining the size and depth of the earthquake,

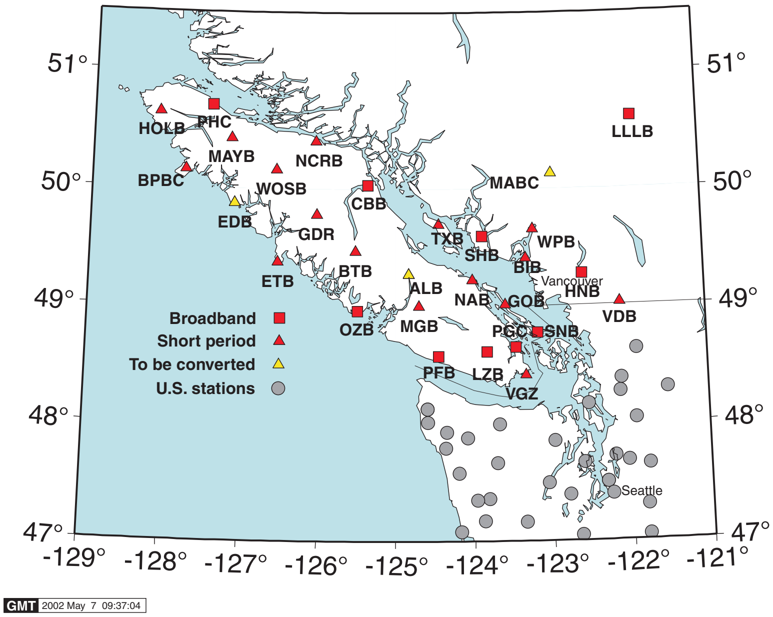


Figure 3.

Continuous-recording seismic sites in southwestern British Columbia. Red squares denote stations with three-component broadband recording; red triangles are sites with only vertical-component short-period recording; yellow triangles represent short-period vertical-component analog stations (to be converted to digital); and grey circles represent seismic stations in the state of Washington.

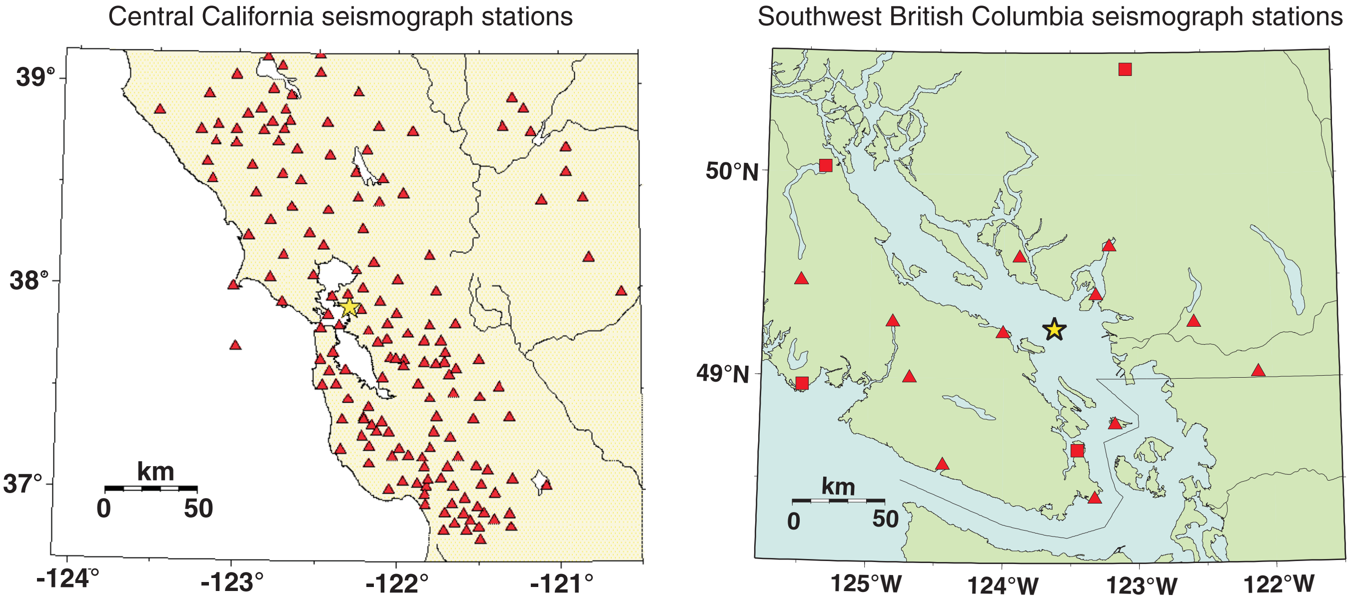


Figure 4. *Comparison of the density of seismic stations in the San Francisco area (left), where ShakeMaps can be produced, to that in southwestern British Columbia (right), where they cannot currently be produced. Maps are plotted at the same scale.*

Figure 5.

Aerial view of Vancouver and Richmond, showing the proposed location of the trial densely spaced seismic network (red box). This area covers rock and firm-soil sites just north of the Fraser River, and the thick soils (up to 800 m thick) near the middle of Richmond.

a press release is issued within an hour of the event. Information, including maps and felt reports, are quickly posted on the Earthquakes Canada website (http://www.earthquakesCanada.ca). Earthquake seismologists at the Sidney and Ottawa offices deal with about 40 to 50 felt, or potentially felt, earthquakes each year, so rapid reporting procedures are tested and used frequently.

FUTURE DIRECTIONS

A focus of NRCan's earthquake monitoring planning is in urban areas, where little or no detailed coverage is currently provided and where significant advances can be made in terms of damage mitigation and emergency response preparedness. Dense networks are required to produce accurate ground-shaking maps. Figure 4 compares the seismograph station spacing in central California, where ShakeMaps (Wald et al., 1999) can be produced, to southwestern British Columbia, where they currently cannot be produced.

Funding from a two-year pilot project will enable the following to be accomplished:

1. A trial, densely spaced, urban, strong ground-motion network of about 60 instruments will be installed in a 7 km by 9 km section of Vancouver and Richmond during 2002–2003 (Fig. 5, 6). The section spans bedrock outcrops, firm soil, and thick, soft sediments of the Fraser River delta. These instruments will be primarily deployed in public buildings (schools, government offices), where power and high-speed Internet connections are more readily available. For a permanent urban network, partners would be sought to help expand the network.
2. Real-time data will be collected from the urban sensors (both the new dense network and existing strong-motion sensors).

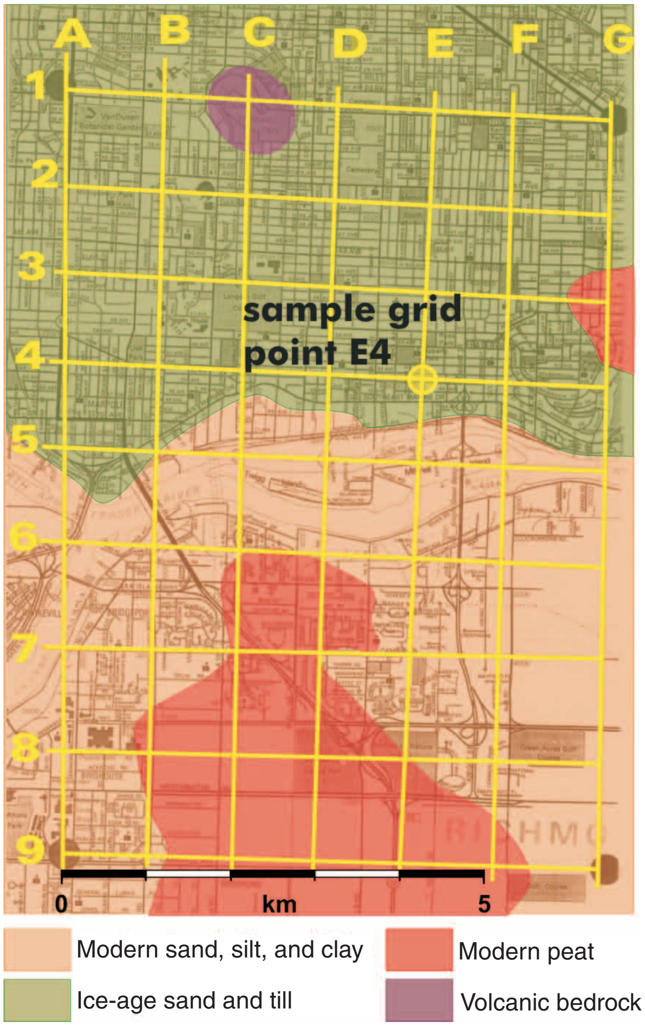


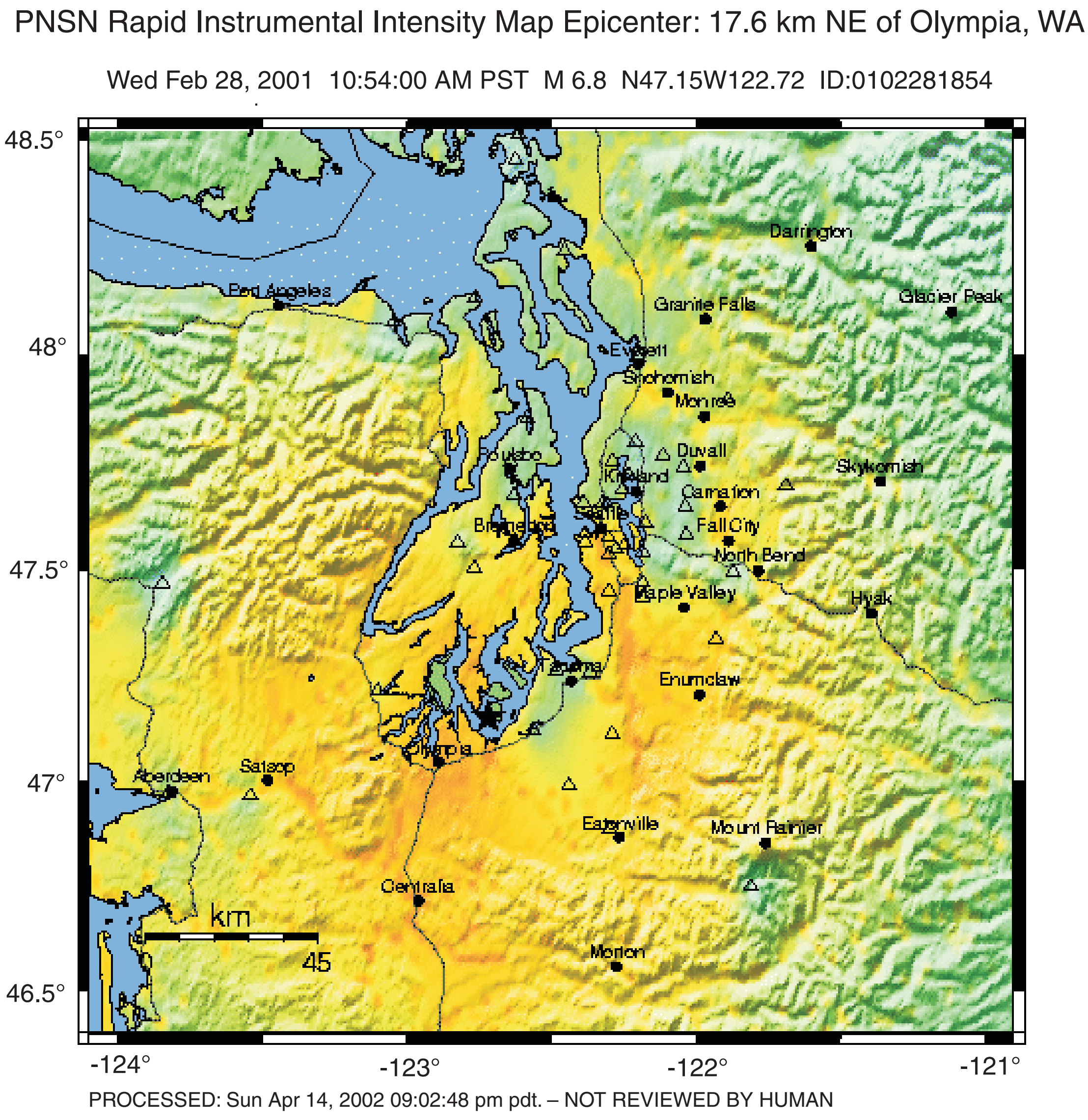
Figure 6. *Proposed grid for dense urban seismograph network in Vancouver-Richmond, British Columbia.*

3. Regional seismic networks surrounding urban areas in southeastern and southwestern Canada will be upgraded and modernized to improve knowledge of the earthquake source, wave propagation, and site response.

New products and opportunities

Data provided in real time from the trial, dense urban seismic network in Vancouver, and from upgrading the existing urban strong-motion network in southwestern British Columbia, will enable the production of accurate shaking maps (e.g. as for the 2001 Nisqually earthquake; *see* Fig. 7) within minutes after potentially damaging earthquakes.

ShakeMaps (Wald et al.,1999; *see* http://www.trinet.org/shake/about.html) are generated using recordings of ground shaking at seismograph sites. ShakeMaps can be generated within a few minutes of an earthquake. The more seismographs that provide recordings of ground shaking, the more accurate these maps will be. All recordings are reduced to a common reference level (a 'rock' site level) and are then



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 7. *ShakeMap for the magnitude 6.8 Nisqually earthquake (generated at the University of Washington).*

interpolated to a uniform grid. Finally, the data are corrected for site amplification (geological) effects (correction factors vary depending on the amplitude and frequency of the shaking) and a smooth function is fit through all grid points. ShakeMaps can be quickly posted on websites, automatically 'pushed' out to key clients (using File Transfer Protocol, FTP), or manually downloaded. The information can be obtained as maps in either GIF or Postscript® format, as tables, or as GIS-formatted maps (shape files). It is important to note that no single shaking map can be used for all purposes. Large buildings and structures will be affected by long-period (low-frequency) shaking, whereas small structures will be affected by short-period (high-frequency) shaking. Current developments underway (Wald et al., 2002) will allow for ShakeMaps to be used with the earthquake-loss estimation program HAZUS (Federal Emergency Management Agency–National Institute of Building Sciences, 1997) for earthquake-scenario planning. HAZUS was developed by FEMA in the United States and is available for use in Canada.

Data from dense urban seismic networks (*see* Adams et al., 2002) could also be used to provide early warning of approaching seismic energy. Such warning systems are currently in place in California, Taiwan, and Japan. They can automatically close key valves or switches to ensure the safe shutdown of critical facilities (e.g. nuclear power plants, electrical power grids, subway systems, and high-speed railway systems).

New research opportunities

Dense urban networks can provide a wealth of new data and research opportunities in seismic hazards:

1. Local site response can be studied to assess how the local geology will affect shaking during future earthquakes.
2. Recordings of small, frequent earthquakes can be used to identify potential amplification 'hot spots', the frequency dependence of amplification, and the variation in duration of shaking at sites.
3. They can facilitate a better understanding of the contribution of two- and three-dimensional structure to ground shaking, and the variation in shaking levels with waves approaching from different directions.

Other research opportunities include examining attenuation levels across urban areas and studying topographic effects.

SUMMARY

Rapid advances in technology and decreasing costs of data collection and transmission are providing a wealth of new opportunities in earthquake monitoring, information, and hazard research. Currently, Natural Resources Canada provides earthquake monitoring and information 24 hours a day, 7 days a week. The current seismic network consists of more than 120 seismograph stations across Canada that continuously record ground shaking and send the data to GSC offices at Sidney and Ottawa in real time. The data are used to quickly locate and determine the magnitude of earthquakes, which are automatically provided to key clients (e.g. CN Rail). Earthquake reports are issued to emergency organizations and the media, and are also posted on GSC websites. The anticipated focus in the near-future is to improve earthquake monitoring capabilities in and around urban areas. Real-time data from dense urban arrays will allow for new products and research opportunities. These products, including 'ShakeMaps', will provide detailed earthquake ground-shaking maps across urban areas. This will assist with rapid emergency response efforts after a major earthquake, and with planning and damage mitigation efforts before an earthquake.

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