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# CANADIAN STRONG MOTION MONITORING AND RECENT DATASETS FROM NATURAL RESOURCES CANADA

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**ABSTRACT:** Strong motion monitoring continues to evolve rapidly in Canada, with many organisations contributing data. This article summarises the current state of strong motion monitoring across Canada, and recent (since 2008) strong motion datasets. As of January, 2015, the Geological Survey of Canada (GSC) – a part of Natural Resources Canada (NRCan), operates 137 strong motion instruments (chiefly Internet Accelerometers or IA's) across Canada, with more than 90 deployed in the urban centres of high seismic hazard in southwest British Columbia (BC). BC Hydro operates more than 80 strong motion instruments at dam sites and substations across BC. The BC Ministry of Transportation and Infrastructure now operates more than 50 free-field and downhole array instruments at or near sites of critical transportation infrastructure. In addition, many of their structures are instrumented (not discussed in this article). Ocean Networks Canada currently has three strong motion instruments on the seafloor west of Vancouver Island, and five along the west coast of Vancouver Island, and the University of British Columbia (UBC) and the British Columbia Smart Infrastructure Monitoring System (BCSIMS) have deployed 28 instruments, primarily at schools in southwest BC. In eastern Canada, NRCan operates 40 strong motion instruments, primarily deployed in the seismically active St. Lawrence and Ottawa Valley regions. Other organisations operating strong motion instruments in eastern Canada include: Hydro-Quebec at 12 dams and a number of substations; Ontario Power Generation and New Brunswick Power at their nuclear power stations; Public Works and Government Services Canada (PWGSC) at Parliament Hill; and Gaz Metropolitain at its Montreal LNG plant. Since 2010, more than 1050 accelerograms have been recorded across Canada, sampling a variety of settings from intraplate (2010 Mw 5.0 Val du Bois, Quebec) to active tectonic regions off the west coast of Vancouver Island (2014 Mw 6.6), and offshore Haida Gwaii (2012 Mw 7.8). While some large earthquakes have been recorded, the strongest ground motions are less than 20%g. Nevertheless, these datasets are still useful for comparison with ground-motion models proposed for hazard modelling purposes, and for evaluating local earthquake site response. The results of these studies are valuable to scientists and engineers evaluating strong ground shaking during future earthquakes.

# 1. Introduction

The purpose of this paper is to provide: 1) a brief overview of the strong motion networks in Canada as of January, 2015; and 2) a summary of recent (since 2008) GSC strong motion network datasets. For details of the history of strong motion instrument deployments in Canada see Milne and Rogers, (1971), Rogers (1976), Rainer and Luctar, (1983), Weichert and Munro (1987), Rogers et al. (1999), Cassidy et al. (2007) and Cassidy et al., 2008. Since the last review by Cassidy et al. (2008) the number of instruments deployed has increased by nearly 40% and now the vast majority of instruments are digital with data available in near-real-time. These modern digital instruments provide high data quality even near their limit of resolution and have adjustable triggers, which means the trigger levels can be optimized based on the local site conditions. The largest networks are the strong motion network operated by the Geological Survey of Canada (137 instruments), British Columbia Ministry of Transportation and Infrastructure (~50 free-field and down-hole instruments and more than 50 additional structural monitoring instruments), BC Hydro, including dams and transmission facilities (81 instruments), UBC (28 instruments), Hydro-Québec (27 instruments), and Ocean Networks Canada (eight instruments). Most of the strong motion sensors are deployed in the earthquake-prone areas of British Columbia and Quebec (Figures 1 – 4). A summary of instruments and owners is provided in Table 1, and a list of recent NRCan datasets is provided in Table 2.

# 2 Strong Motion Networks – Western Canada

As of January, 2015, more than 267 strong motion instruments were operating across British Columbia (Figure 1). A brief description of the instruments operated by various organisations is provided below. It is noteworthy that, at this time, more than half of these instruments (e.g., those operated by GSC and BC MoTI) are interconnected through the BC Smart Infrastructure Monitoring System – BC SIMS (http://www.bcsims.ca/).

## 2.1 Geological Survey of Canada (Natural Resources Canada)

The GSC strong motion network in western Canada is comprised of 95 Internet Accelerometers (IA's) and two Titan's deployed in British Columbia (Figure 1). The IA's are connected to the internet and record data continuously, rather than in "triggered mode". They continuously compute a suite of ground parameters (e.g., PGA, PGV, PGD, and Katayama Spectral Intensity) and provide waveforms in miniseed format. These waveform data can be retrieved at any time via the internet. For more details of the IA, see Rosenberger et al (2007) or http://www.earthquakescanada.nrcan.gc.ca/stndon/CNSN-RNSC/sm/IA_Details-eng.php (last accessed, April, 2015). The goal is to acquire strong ground motion records in or near urban environments and to define strong motion attenuation relationships in western Canada. There is also a focus on acquiring ground motion records on the soft soils of the Fraser River delta, and the Georgia Basin area to better assess the role of surficial soils, and deep basin structure (e.g., Molnar et al., 2014) in earthquake ground shaking. GSC IA's are deployed in schools, surface vaults, or small buildings to provide near free-field recordings.

Prior to the 2012 Mw 7.8 Haida Gwaii earthquake, three strong motion instruments were operating in the BC north coast region (two on Haida Gwaii, and one at Prince Rupert – see Rosenberger et al., 2013). Immediately following the earthquake additional strong motion sensors were deployed at Mitchell Dam (HG1B) and seismic station DIB, both on the west coast of Moresby Island, and Jedway (HG4B) on the southeast coast of Moresby Island.

Over the coming 3-4 years the Canadian National Seismic Network (CNSN) will be modernised. Associated with this major upgrade will be the addition of strong motion instrumentation to many of the (weak-motion) seismograph stations in high-hazard regions and selective updating of older strong motion instruments in other locations.

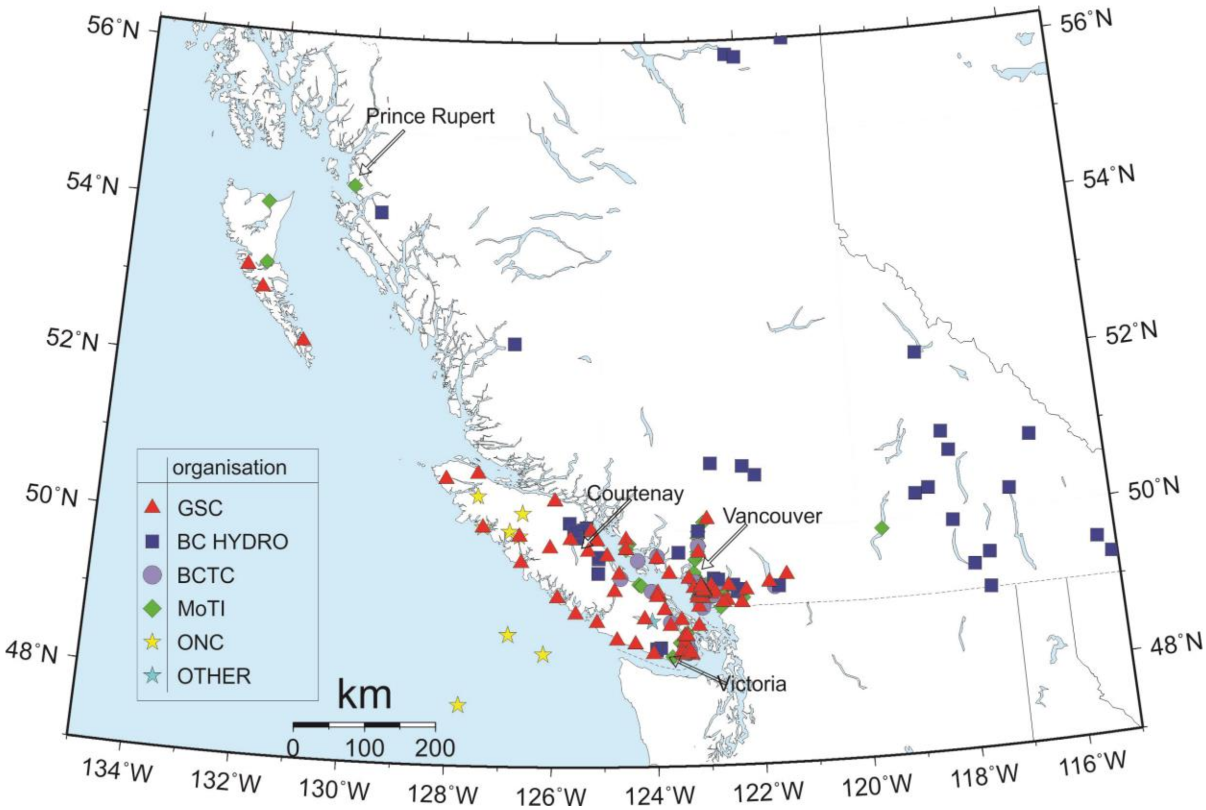


**Fig. 1 – Strong motion seismographs in western Canada.**

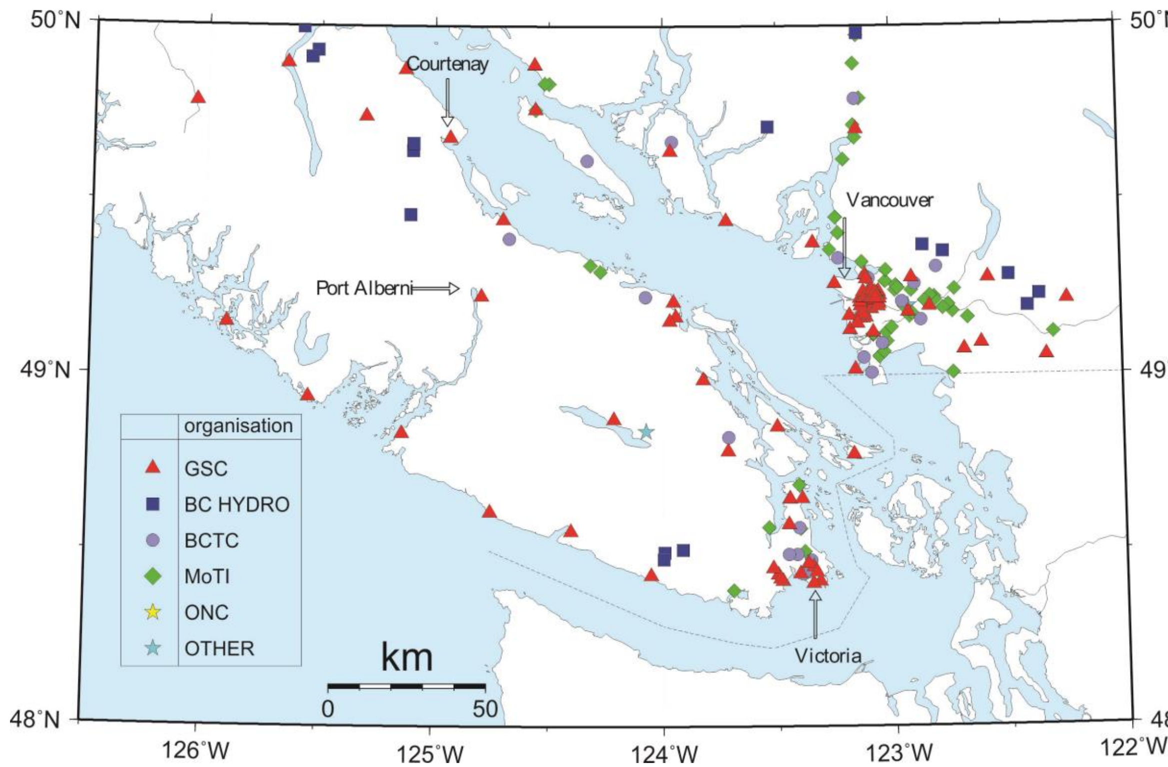


**Fig. 2– Onshore strong motion seismographs in southwest British Columbia**

Lower Mainland Strong Motion Seismograph Sites

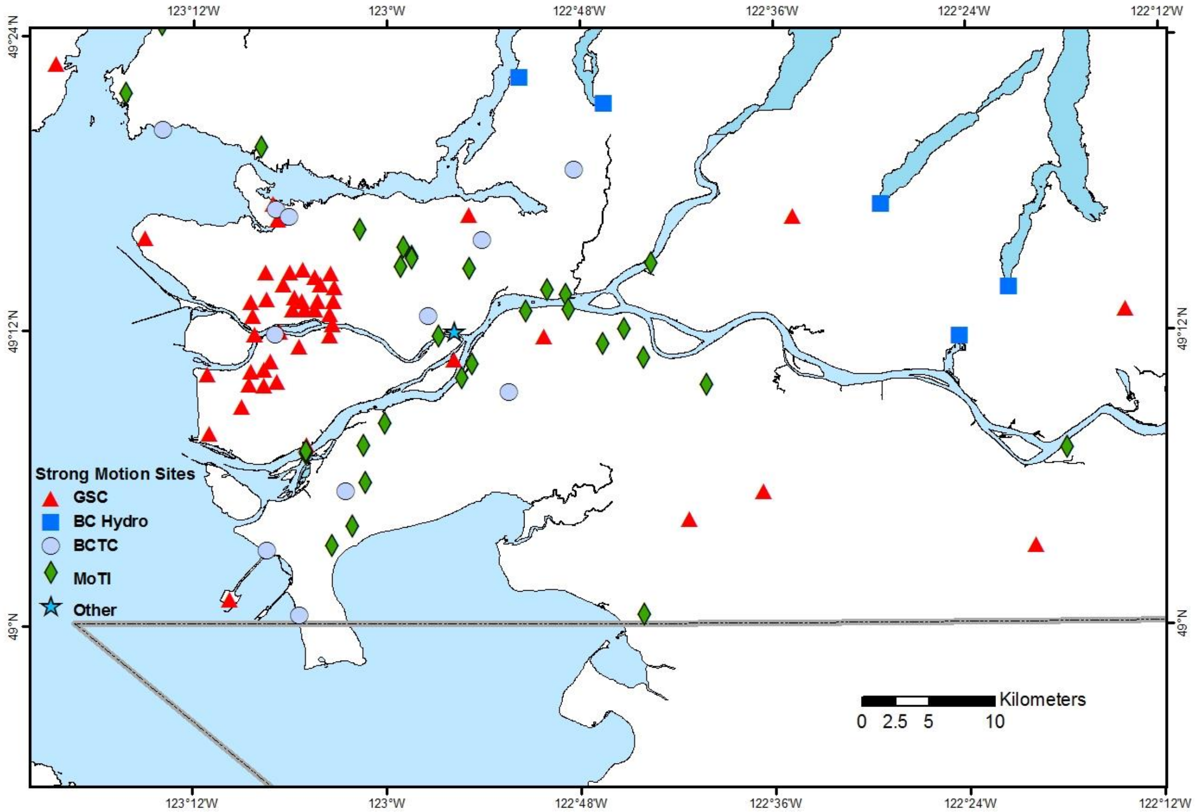


**Fig. 3– Strong motion seismographs in Greater Vancouver and the lower mainland.**

## 2.2 BC Hydro and Transmission

The BC Hydro strong motion network in British Columbia has been expanded since 2007. BC Hydro maintains 81 instruments at most hydroelectric dams and transmission facilities across the province (Figures 1-3). These instruments provide data for both the dam safety program (e.g., for post-earthquake dam performance) and the transmission program (e.g., post-earthquake analysis of transmission facility performance). A total of 58 instruments operate at 31 dam facilities (labelled "BC Hydro" in Figures 1-3), with multiple instruments often installed at a dam site in locations such as the crest, abutment or toe (in a few cases on foundation bedrock). In addition, there are 15 seismic triggers that provide notification of shakings exceeding target threshold levels. Of these 58 instruments, most are digital SYSCOM MR202 units, with 2-g full scale, and trigger thresholds of about 0.5%g. A total of 23 instruments are deployed (labelled "BCTC" in Figures 1-3) at transmission facilities (major substations and terminal stations – most are on soil and in urban settings). These are all SSA-2's or ETNA's, 2-g full scale with trigger thresholds of either 0.4%g or 0.6%g.

None of the BC Hydro and Transmission instruments currently provide data in real-time. There are plans to upgrade and improve this monitoring network over the next several years.

## 2.3 BC Ministry of Transportation and Infrastructure

The BC Ministry of Transporatation and Infrastructure (BC MoTI) has expanded and densified its strong motion monitoring network (labelled "MoTI" in Figures 1-3) in recent years and is in the process of improving visualisation software and web access to information (including shakemaps). The purpose of this expansion is to contribute to situational awareness at the time of an earthquake (providing shakemaps and ground shaking parameters for BC MoTI and emergency responders), and, much like

ShakeCast (e.g. Wald et al., 2008), to prioritise infrastructure inspections and aftershock response, and to provide data in real-time that may be useful for other applications such as earthquake early warning.

In addition to monitoring key bridges and transporatation infrastructure, strong motion instruments have been deployed at some schools and BC Housing facilities, and are being added at remote “DriveBC” sites with power and internet. As of January, 2015, 51 strong motion seismographs are operating (in free-field conditions) and many more instruments are operating on key structures (e.g., the new Port Mann Bridge has a total of 350 channels, and the Second Narrows Bridge has 122 channels). The majority of the free-field strong motion sensors are IA’s. In addition, BC MoTI has deployed five new downhole strong motion arrays on the Fraser River delta just south of Vancouver (two arrays on the South Fraser Perimeter Road project, and three downhole arrays near the Port Mann Bridge). These data are combined with those of other organisations and are available via the British Columbia Smart Infrastructure Monitoring (BCSIMS) project. Future plans including adding (up to ~10) DriveBC sites, partnering with the City of Vancouver for bridge monitoring, and perhaps adding GPS data to generate displacement maps.

### 2.4 Ocean Networks Canada (ONC)

Ocean Networks Canada (including the offshore NEPTUNE observatory) now operates a total of eight strong motion instruments in southwest BC: three Guralp strong motion seafloor instruments deployed as a part of the NEPTUNE project off the west coast of Vancouver Island (Figure 1), and five land-based instruments on the west coast of Vancouver Island. Three of the five accelerometers on Northern Vancouver Island will be replaced by Nanometrics Titan SMA’s and ONC also intends to install three Nanometrics Titan EA’s underwater on the NEPTUNE system by 2016. These strong motion data will be used for applications to earthquake and tsunami early warning (e.g., see Pirenne et al., this volume).

### 2.5 University of British Columbia – BCSIMS

The University of British Columbia (Department of Civil Engineering – Earthquake Engineering) is a leading contributor to the BCSIMS project (Kaya et al., 2014). BCSIMS integrates strong motion data from a number of agencies to produce shakemaps and near-real time ground motion information; UBC contributes P-wave detectors and methods to the ONC “WARN” project (Pirenne et al., 2014) and has deployed (starting in 2014) instruments in schools across southwestern BC as part of a prototype earthquake early warning system. Currently 28 instruments (not linked with BCSIMS at this time) are deployed, with an additional 10-12 to be deployed during 2015.

### 2.6 Other

FortisBC Gas (formerly Terasen Gas) operates two strong motion instruments at the Tillbury Island LNG plant, just south of Vancouver.

## 3 Strong Motion Networks – Eastern Canada

As of January, 2015, approximately 80 strong motion instruments are operational in eastern Canada. There have been no substantive changes to strong motion monitoring networks here since the last review in 2008 (Cassidy et al., 2008). A very brief summary is provided below.

The GSC operates an eastern regional network of 40 instruments (many in the vicinity of the seismically-active Charlevoix region – see Figure 4) to gather near-field strong motion data and to help define strong ground motion attenuation relations for eastern Canada. The current GSC strong motion network consists of eight IA’s (four deployed in Montreal and four in Ottawa), two Titan’s, and 30 ETNA’s (six of which are co-located with weak motion seismographs in Charlevoix, QC). For additional instrumentation and processing details up to 2010, see Lin and Adams (2012a). In a joint deployment with Carleton University, the GSC has instrumented several deep-soil basins near Ottawa together with a nearby rock reference site for periods of a few years.

As well as the listed mainshock records (which are often from triggered instruments) the GSC installed continuous-recording Titan accelerometers for limited time periods to record aftershocks from the Val-des-Bois (stations VABQ and VDBQ) and Ladysmith (LDSQ) earthquakes (as well as for the 2012 Haida Gwaii and 2010 Haiti earthquakes). The continuous records are available by request to the GSC’s National Waveform Archive. Over the coming 3-4 years the Canadian National Seismic Network (CNSN) will undergo a modernisation. Associated with this major upgrade will be addition of continuous-recording strong motion instrumentation to many of the (weak-motion) seismographs in high-hazard regions and selective updating of older strong motion instruments in other locations.

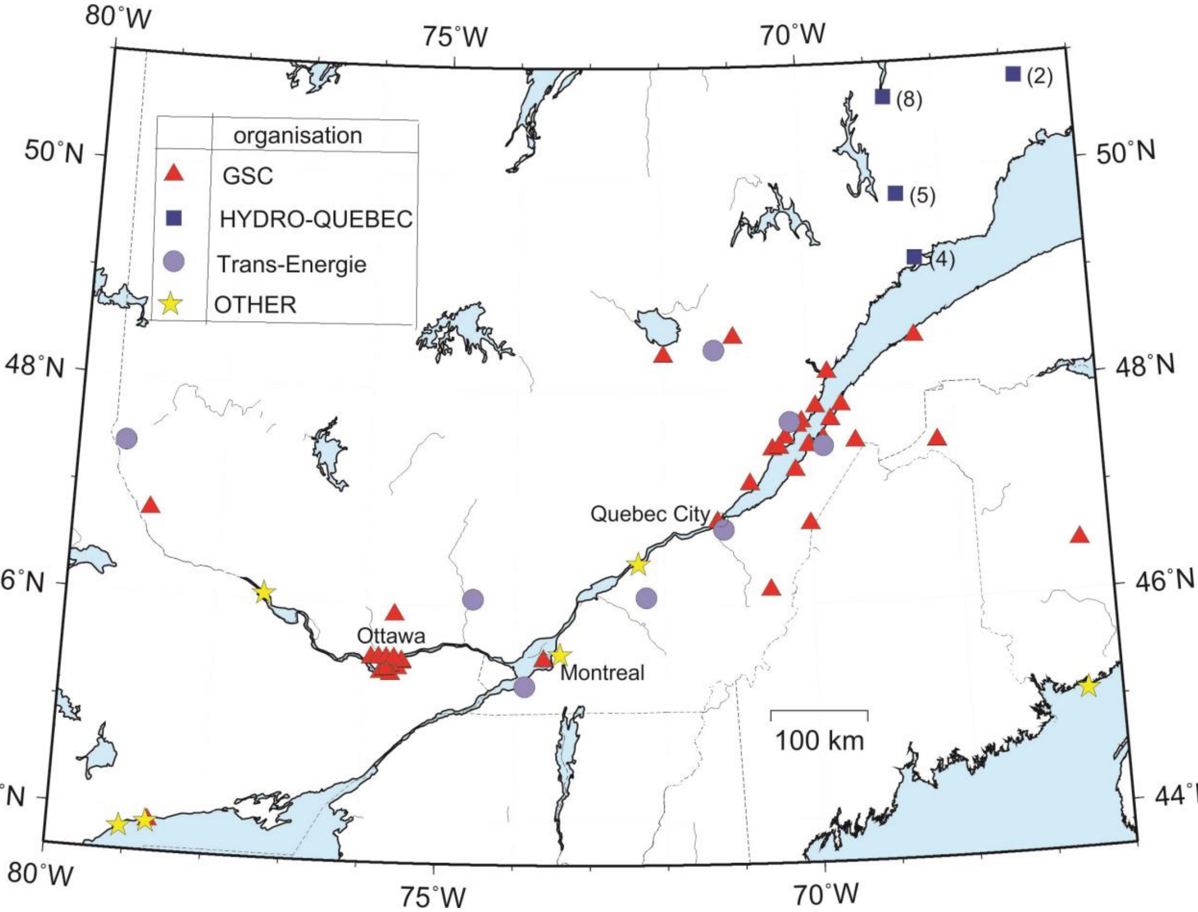


**Fig. 4 – Strong motion seismographs in eastern Canada. Numbers in parenthesis at Hydro-Quebec sites indicate the total number of instruments at each facility.**

Strong motion instruments are also operated by Hydro-Québec and Trans-Energie. Their instruments are installed at key hydroelectric dams and transformer sub-stations (Figure 4) as a part of their overall permanent seismic monitoring program that includes a network of 12 seismographs telemetered to Ottawa in real-time. The former provide free-field and structural response for Hydro-Québec dams, while the response of the overburden at Trans-Energie's transformer stations, one of which was seriously damaged during the 1988 Saguenay earthquake, is monitored by the latter. Most of the 27 sites are fitted with Kinemetrics SSA-1's (1 or 2g) or 2g ETNA's, while one dam remains instrumented with eight analogue SMA-1 1g units. Ontario Power Generation and New Brunswick Power operate triggered strong motion instruments in and (for free-field motions) near their nuclear power plants in Ontario and New Brunswick, respectively, and Gaz Metropolitian Inc. has a free field digital accelerograph installed at their LNG plant in Montreal.

**Table 1. Strong motion instruments deployed in Canada (as of Jan. 2015).**

| Owner | Analogue | Digital | Total |
|---|---|---|---|
| GSC West | - | 97 | 97 |
| BC Hydro | - | 58 | 58 |
| BCTransmission | - | 23 | 23 |
| BC MoTI | - | 51 | 51 |
| UBC | - | 28 | 28 |
| ONC | - | 8 | 8 |
| Other West* | - | 2 | 2 |
| GSC East | - | 40 | 40 |
| Hydro-Québec | 8 | 19 | 27 |
| Other East* | - | 13 | 13 |
| **Total – All of Canada** | **8** | **339** | **347** |

*these numbers may not be complete as we have not surveyed all potential owners.

## 4 Recent NRCan Accelerograms

Since the last review of strong motion networks in Canada by Cassidy et al. (2008), more than 1000 seismic waveforms have been recorded by strong motion instruments across the country. Table 2 lists the most significant events (or other “events of interest” such as the McAdam, NB earthquake). Additional digital eastern records (complete to 2010) are listed in Lin and Adams (2012a). Almost all of the events in Table 2 yielded “weak shaking” recordings (1-5%g), however some significant datasets resulted. The strongest shaking recorded (nearly 20%g) was at the Village of Queen Charlotte (QCC) on Moresby Island during the 2012 M 7.8 Haida Gwaii earthquake (Allen and Brillon, 2015; Bird and Lamontagne, 2015). In eastern Canada, the 2008 Riviere-du-Loup earthquake provided an exceptional set of near-field records (Lin and Adams, 2012b). Later, the 2010 Val-des-Bois earthquake produced the strongest shaking in Ottawa in more than 150 years, providing a rich (but relatively low-level) strong motion dataset for free-field sites. The strongest free-field shaking in the Val-des-Bois dataset is ~9%g on a thick soil site (Lin and Adams, 2010; 2011); as well in-structure records giving the seismic response of three towers on Parliament Hill were obtained (Lin et al. 2011). Although not of engineering significance, records with a PGA of 9%g from an earthquake of magnitude ~1 at a distance of less than 1 km were recovered from the 2012 McAdam earthquake swarm (Butler et al., 2013). The 2013 Ladysmith earthquake produced a dataset (largest PGA of 3.9%g at the GSC-Carleton soil site) that was useful to evaluate local site response in Ottawa (Bent et al., 2015).

## 5. Conclusions

Strong motion monitoring continues to evolve rapidly across Canada, with additional organisations now contributing data, and increasing and varied applications for these data. As of January, 2015, more than 347 (near free-field) strong motion instruments are deployed across the country. These data will be used to better understand ground motions and improve situational awareness following major earthquakes (e.g., more accurate shakemaps), and may contribute to the development of earthquake early warning systems in some areas. Significant datasets from the NRCan strong motion network since 2008 include recordings of the 2012 M 7.8 Haida Gwaii earthquake (shaking just under 20%g) and its aftershocks, and recordings of the 2010 Val-des-Bois and 2013 Ladysmith earthquakes, with shaking levels up to 9%g. These datasets have been used to help evaluate earthquake site response and improve ground motion attenuation relationships in Canada. Fully characterising the sub-surface properties at strong motion sites across Canada would further advance ground-motion model evaluation and development.

**Table 2. Recent NRCan data sets from strong motion seismographs in Canada.**

| Earthquake | Date | Location (Lat, Lon) | Magnitude | Number of Records |
|---|---|---|---|---|
| **Riviere-du-Loup, QC** | **2008/11/15** | **47.73N, 69.73W** | **$M_N$ 4.2** | **66** |
| **Victoria, BC** | **2009/06/06** | **48.40N, 123.50W** | **$M_L$ 2.2** | **84** |
| **Val-des-Bois, QC** | **2010/06/23** | **45.90N, 75.50W** | **$M_w$ 5.0** | **165** |
| **Hawkesbury, ON** | **2011/03/16** | **45.58N, 74.55W** | **$M_N$ 4.3** | **27** |
| **Offshore Vancouver Island, BC** | **2011/09/09** | **49.34N, 127.26W** | **$M_w$ 6.3** | **192** |
| **McAdam, NB** | **2012/03/23** | **45.59N, 67.32W** | **$M_N$ ~1** | **6** |
| **St. Amable, QC** | **2012/10/10** | **45.69N, 73.20W** | **$M_N$ 4.5** | **27** |
| **Haida Gwaii, BC*** | **2012/10/28** | **52.62N, 132.10W** | **$M_W$ 7.8** | **9*** |
| **Hawkesbury, ON** | **2012/11/06** | **45.60N, 74.59W** | **$M_N$ 4.2** | **24** |
| **Ladysmith, QC** | **2013/05/13** | **45.74N, 76.35W** | **$M_N$ 5.2** | **27** |
| **Offshore Vancouver Island, BC** | **2014/04/24** | **49.64N, 127.73W** | **$M_W$ 6.6** | **231** |
| **Tofino, BC** | **2015/01/08** | **49.18N, 125.72W** | **$M_w$ 4.4** | **192** |

*Note that the 2012 Haida Gwaii strong motion records are from the BC MoTI network.


## 6 Acknowledgements

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