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THE NEW REAL TIME REPORTING STRONG MOTION SEISMOGRAPH NETWORK IN SOUTHWEST BC: MORE STRONG MOTION INSTRUMENTS FOR LESS MONEY

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ABSTRACT

In 2001, the Geological Survey of Canada started building a modern strong motion seismograph network in southwestern British Columbia, which has now grown to more than 100 instruments. Our experience shows that a dense network of real-time communicating instruments does not have to be associated with high initial investments and can be operated with a modest budget. This paper presents details of the instrument employed, the design of the new network and the performance of real time client information systems.

Introduction

There are very few recordings from strong earthquakes in Canada to provide the basis for design spectra used in earthquake engineering and ultimately in the performance based design of structures. The rather small database of strong ground motion recordings is mainly due to the lack of instrumentation in high seismic risk areas. The inherent uncertainty of design spectra may lead to over-design, or in the worst case, to the construction of structures with insufficient seismic resilience.

The 1994 Northridge, USA, and the 1995 Kobe (Hyogo-Ken Nanbu), Japan, earthquakes are credited to have prompted a drastic paradigm shift in strong motion seismology. In order to capture such key data of engineering importance modern strong motion networks should provide a dense grid of instrument locations able to sample the amplification variation due to small scale variations in local surface geology in urban areas. Modern communication technologies additionally provide the opportunity to monitor ground motion parameters, such as peak ground acceleration, velocity and spectral intensity in real time and relay this information to disaster management agencies, critical infrastructure and lifeline operators within seconds after an earthquake, providing a new function for strong motion networks.

In western Canada the principal high seismic hazard area stretches along the Pacific coast of the province of British Columbia (Rogers, 1998), where seismic risk is concentrated in a few urban areas (Fig. 1). In 2001 the Geological Survey of Canada (GSC) began a program to improve its strong ground motion monitoring capability in the southwestern part of British Columbia, which at that time consisted of about thirty-five instruments without telemetry, mainly vintage (analogue) strong motion seismographs (Rosenberger et al., 2004, Rogers et al., 1999). The instruments were too sparsely distributed to generate a sufficient database of strong motion waveforms needed by the engineering community for structural and geotechnical design. The network also did not meet the current requirements of a modern seismic information system (National Research Council, 2006) capable of a rapid, near real time response that could rapidly identify the most affected areas in the in case of a large earthquake.

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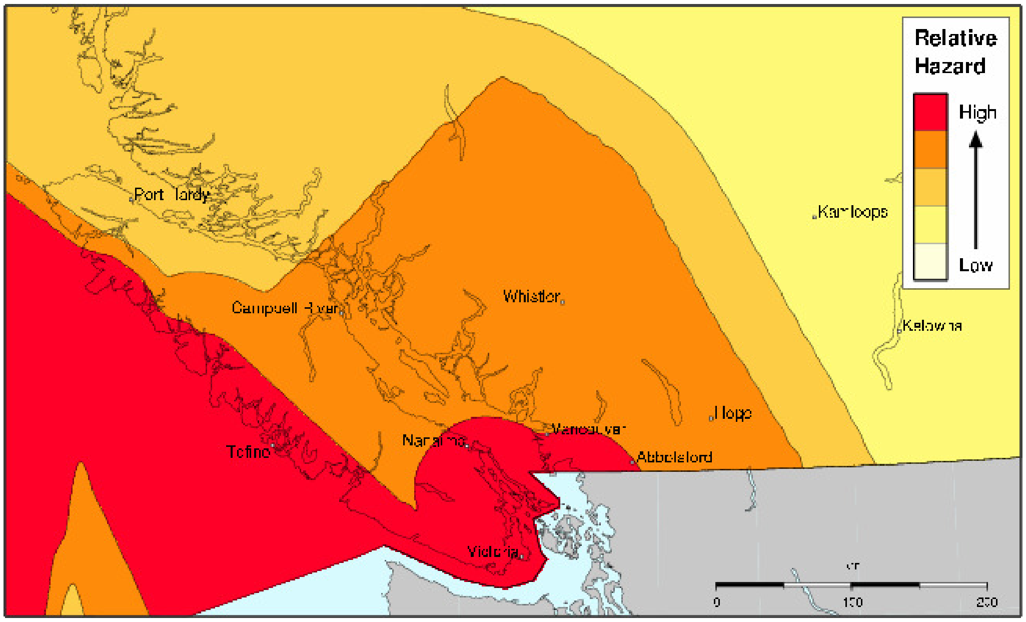

Figure 1. The 2005 seismic hazard map for Southwest British Columbia. The dark red area represents peak ground acceleration of 0.6g with a probability of exceedence of 2% in 50 years (adapted from Adams and Halchuk, 2003).

The GSC Internet Accelerograph

The GSC adapted the paradigm that station density was more important than sensitivity of an individual instrument. This means that the majority of the new instruments would be spatially distributed according to seismic risk, i.e. would be densely deployed in a high hazard region in an urban environment, which has a high culturally generated seismic noise level.

The instrumentation to achieve our network modernization program at a reasonable price was not available commercially. We chose to design a compact, "all in one" instrument, which encompasses sensors, digitizer and single board computer (SBC) to handle signal processing, data storage and TCP/IP communications. The digitizer acquires 18 bit, 100 samples per second acceleration data from three orthogonal sensors which are then stored in 5 minute records. The commercial version of this instrument is now available with a RMS noise floor of either 500µg or 50µg and a range of +-3g and +-2g respectively for less than $2,500. The instrument is designed to have a permanent Internet connection and achieves absolute (UTC) time synchronization with less than 10 ms error using network time servers (Mills, 1997).

Full waveform data are acquired continuously into a ring-buffer of 36 hour capacity. The integrated SBC provides signal-processing capacity to compute derivative data such as velocity and a spectral intensity estimate (Katayama et al., 1998; Elenas, 2002) continuously and in real time (Kanamori et al., 1999). Continuously computed values of short term and long term average ratios are used in a noise adaptive triggering scheme (STA/LTA trigger). Once triggered, peak values of acceleration (PGA), velocity (PGV) and spectral intensity (PSI) are determined over an observation time interval and if peak spectral intensity exceeds a pre-set threshold, waveform data are additionally stored in non volatile (flash) memory.

A Fully Telemetered Strong Motion Network

The new strong motion instruments are designed to connect to the Internet through any local area network connection. The physical means to connect the instrument to the Internet are not limited to classic wired Ethernet. Instruments in the current network are routed to the Internet through the Ethernet over power-line bridges, spread-spectrum radio links, satellite and wireless local area connections. Ethernet to cellular-data to Internet routers are also readily available and are currently used to connect two instruments on remote locations owned and operated by a highway maintenance company.

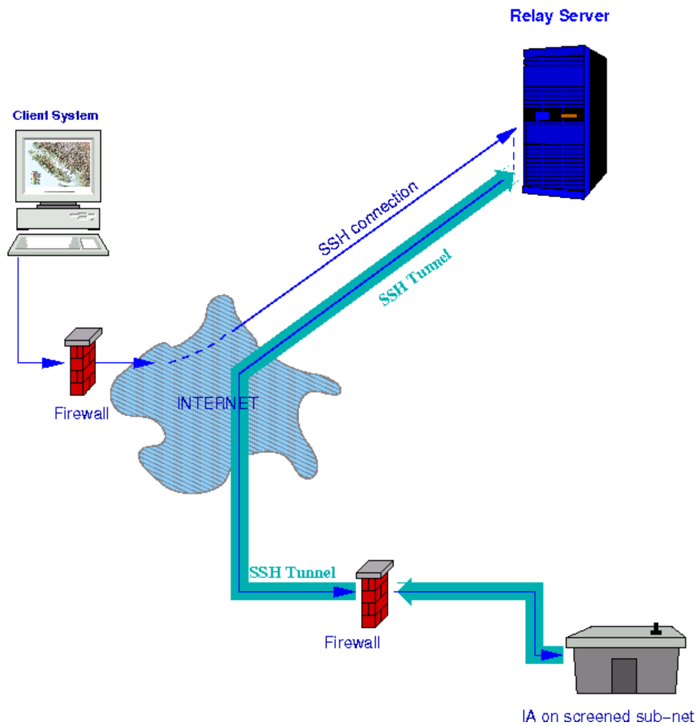

Figure 2. Basic building blocks of the network. A relay maintains authenticated and encrypted tunnel connections with an instrument. Client systems connect to a unique port on the relay and are forwarded to a specific instrument to retrieve waveform data. The relay serves as a repeater for parametric ground motion reports.

The instrument is designed to fit into almost any local area network configuration. It can operate without problems from behind a firewall or network address translating (NAT) router. Several of our instruments operate in security sensitive environments and have passed an external network security audit as well as the test of time: there has not been a single security related incident over the in four years of operation.

The capability of an instrument to compute and report ground motion parameters is crucial for the network design and operation: The continuous real-time transmission of full-waveform data to a data-centre is not required for a first assessment of ground motions across the network. Brief parametric ground motion reports can be directly forwarded to client systems for evaluation.

The communication bandwidth required by an instrument is extremely low in normal operation; on average less than 25 bits/sec since full waveform data is not transmitted. Thus, the instrument has no measurable impact on a local network. In British Columbia this strong motion seismograph network does not generate any communications costs at the instrument locations. All GSC instruments are hosted at no charge on third party Internet connections, including private, residential DSL/Cable, and satellite connections.

We use a so-called relay server to maintain tunnelled connections to the instruments and to re-distribute event reports sent from an instrument. As illustrated in Fig. 2, the use of a relay facilitates the communication with instruments that are on private networks that are screened by a firewall or a network address translation router. The instruments actively establish a connection to the relay. An application wanting to communicate with an instrument can pick up the connection at the relay server. All connections are authenticated and encrypted.

A total of three relay servers are used in our network. Two relays are located outside the high seismic hazard area and serve as back-up systems in the event of a large earthquake affecting the coastal region. Two relays are equipped with a GPS clock and provide time to most instruments via the network time protocol (NTP) service.

Physically, a relay is nothing but CD-Rom based software, which boots any standard PC-style hardware into a single purpose application. This has proven to be a secure and reliable way to organize communications and scales well with large numbers of instruments. One relay can handle several hundred instruments. It does not require any routine maintenance.

Relay servers are used to distribute the information to a larger number of clients and limit the amount of data traffic from an individual instrument; they also provide the hinge for TCP/IP tunnels for direct control of the instruments. However, they are not required in a basic network.

Network Performance in a Small Earthquake

On January 15, 2006 many people in the southern parts of Vancouver Island, British Columbia, woke up to a magnitude 3.9 earthquake, which occurred at 4:30 a.m. PST (12:30 UTC), 20 km northwest of the city of Victoria, at a depth of 50 km. Thirty instruments are deployed in the southern Vancouver Island area, 18 of those are located in the greater Victoria area (Fig. 3).

The box in Fig. 4 shows instrument reports as they were logged arriving at one of three computers which then relayed the messages to client systems. Time-stamps were assigned by both the relay at the time of reception and the reporting instrument at the time the message was emitted. Latency is less than a second for most messages.

The instruments report twice: A first message reports that the instrument has triggered, then, after a post-trigger observation time has passed, a second message with the observed peak ground motion values is issued. Our instruments report acceleration in fractions of the earth's acceleration, g, computed values of velocity and spectral intensity are referenced to g as well. The instruments "PGC01NA" (14.2 km from the epicentre) and "SDN01NA" (16.6 km from the epicentre) are less than 6 km distant from one another (Fig. 3 and Fig. 5). "PGC01NA" is located in the seismic vault of the Pacific Geoscience Centre while "SDN01NA" is in the noisier environment of the town of Sidney's municipal hall. From looking at the time-stamps of the reports from both instruments it can be seen that the PGC instrument triggered on the P-wave arrival, while "SDN01NA" triggered on the larger amplitude S-wave. This is to be expected since the trigger-threshold of the Sidney municipal hall instrument is adapted to the noisy site and the P-arrival did not reach that threshold.

The largest peak acceleration value of about 1% g is reported by one of the Victoria urban instruments (VCT03NA, 20.5 km from the epicentre) which also reports the largest peak spectral intensity value of about 0.4 cm/sec^2 (in Katayama (1998) units). This instrument is installed in a private residence located on a soil site known to amplify seismic waves (Monahan et al., 1998, Molnar et al., 2004).

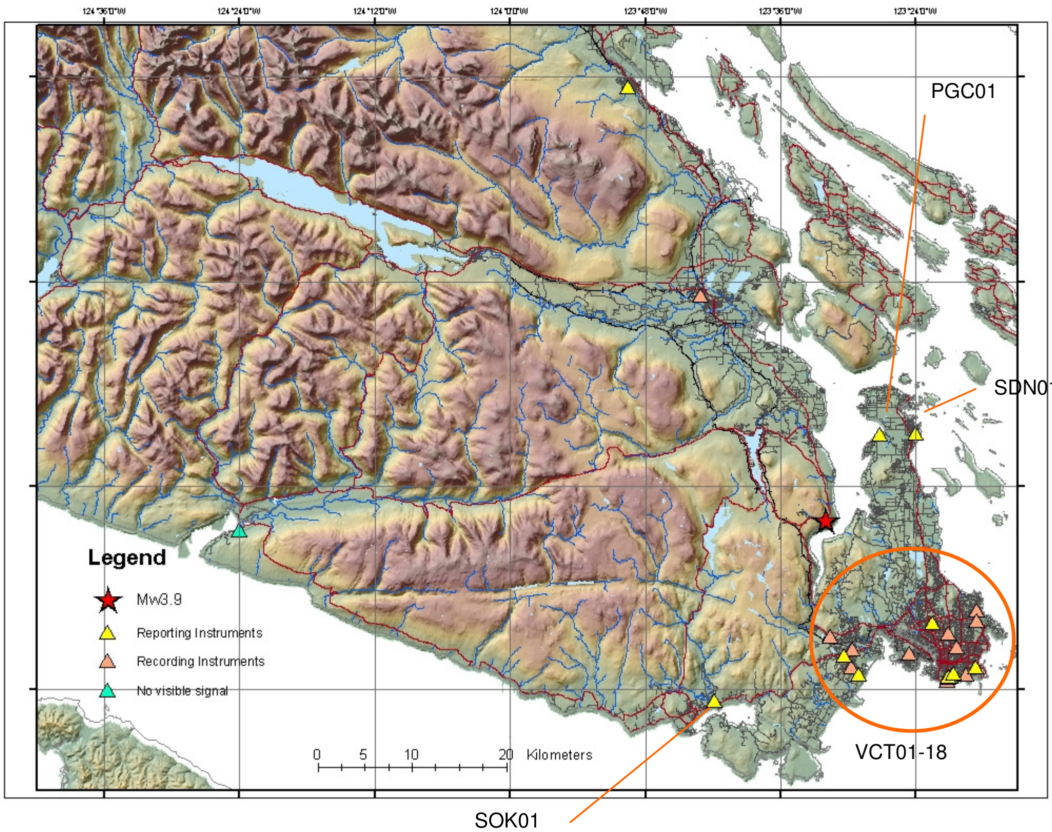

Figure 3. Southeast tip of Vancouver Island and the greater Victoria area (circle). The epicentre of the magnitude 3.9 earthquake is marked with a red star. Yellow triangles mark instruments which detected the event and reported ground motion parameters. Instruments which recorded the event but did not have sufficient amplitude to automatically report parameters are shown as orange triangles. Instrument locations discussed in the text are labeled.

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Jan 14 17:47:10: VCT04NACN *** Triggered Sun Jan 15 01:47:10 2006 , waiting for data ...
Jan 14 17:48:10: VCT04NACN Sun Jan 15 01:47:10 2006 -Event parameters PGA 1.0575e-02, PGV 4.6893e-04, PGD 4.2060e-04, kSI 5.7849e-04
Jan 14 20:05:58: WHS01NACN *** Triggered Sun Jan 15 04:05:58 2006 , waiting for data ...
Jan 14 20:06:58: WHS01NACN Sun Jan 15 04:05:58 2006 -Event parameters PGA 1.9865e-02, PGV 7.7274e-04, PGD 4.2796e-04, kSI 1.0538e-03
Jan 14 23:29:49: VCT08NACN *** Triggered Sun Jan 15 07:29:49 2006 , waiting for data ...
Jan 14 23:30:49: VCT08NACN Sun Jan 15 07:29:49 2006 -Event parameters PGA 1.6838e-02, PGV 1.2673e-03, PGD 4.0877e-04, kSI 2.4747e-03
Jan 15 04:29:54: PGC01NACN *** Triggered Sun Jan 15 12:29:54 2006 , waiting for data ...
Jan 15 04:29:58: SDN01NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:29:58: VCT14NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:29:58: VCT17NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:29:59: VCT03NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:04: VCT11NACN *** Triggered Sun Jan 15 12:29:58 2006 , waiting for data ...
Jan 15 04:30:04: SOK01NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:05: VCT01NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:05: VCT04NACN *** Triggered Sun Jan 15 12:29:59 2006 , waiting for data ...
Jan 15 04:30:05: LDY01NACN *** Triggered Sun Jan 15 12:30:04 2006 , waiting for data ...
Jan 15 04:30:11: VNC19E3CN *** Triggered Sun Jan 15 12:30:11 2006 , waiting for data ...
Jan 15 04:30:58: SDN01NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 9.8580e-03, PGV 4.9888e-04, PGD 4.4868e-04, kSI 6.5753e-04
Jan 15 04:30:58: VCT17NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 5.8614e-03, PGV 4.3085e-04, PGD 3.9501e-04, kSI 5.7685e-04
Jan 15 04:30:58: VCT11NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 1.0618e-02, PGV 5.5440e-04, PGD 4.8871e-04, kSI 5.9432e-04
Jan 15 04:30:58: VCT14NACN Sun Jan 15 12:29:58 2006 -Event parameters PGA 1.3837e-02, PGV 6.4166e-04, PGD 4.9910e-04, kSI 6.8502e-04
Jan 15 04:30:59: VCT04NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 5.1100e-03, PGV 4.6578e-04, PGD 3.7877e-04, kSI 7.2124e-04
Jan 15 04:30:59: VCT03NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 1.0279e-02, PGV 5.0312e-04, PGD 3.8180e-04, kSI 1.0052e-03
Jan 15 04:30:59: VCT01NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 6.1010e-03, PGV 5.3726e-04, PGD 4.4226e-04, kSI 5.8064e-04
Jan 15 04:31:11: VNC19E3CN Sun Jan 15 12:30:11 2006 -Event parameters PGA 3.6962e-03, PGV 4.5077e-04, PGD 3.1260e-04, kSI 6.7338e-04
Jan 15 04:31:24: PGC01NACN Sun Jan 15 12:29:54 2006 -Event parameters PGA 3.3991e-03, PGV 8.2866e-05, PGD 3.9088e-05, kSI 1.6015e-04
Jan 15 04:31:29: SOK01NACN Sun Jan 15 12:29:59 2006 -Event parameters PGA 1.3690e-02, PGV 6.5612e-04, PGD 4.5142e-04, kSI 6.7652e-04
Jan 15 04:31:34: LDY01NACN Sun Jan 15 12:30:04 2006 -Event parameters PGA 4.8901e-03, PGV 4.7656e-04, PGD 4.4859e-04, kSI 6.4765e-04
Jan 15 10:28:39: BWN01NACN *** Triggered Sun Jan 15 18:28:39 2006 , waiting for data ...
Jan 15 10:30:09: BWN01NACN Sun Jan 15 18:28:39 2006 -Event parameters PGA 6.1532e-03, PGV 4.7546e-04, PGD 3.8555e-04, kSI 5.9018e-04
Jan 15 11:01:48: VCT16NACN *** Triggered Sun Jan 15 19:01:48 2006 , waiting for data ...
Jan 15 11:02:48: VCT16NACN Sun Jan 15 19:01:48 2006 -Event parameters PGA 7.1192e-03, PGV 6.3187e-04, PGD 3.8531e-04, kSI 8.3782e-04
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Figure 4. Trigger-messages and ground motion parameter reports as they were logged during the January 15, 2006 event. The highlighted blocks pertain to the event. Close proximity in time distinguishes the set from spurious triggers, which occur frequently in a noisy urban environment. Note that the initial trigger occurred 8 seconds after the earthquake origin time of 12:29:46 UTC.

Vertical component waveforms are shown on a time-distance plot in Fig. 5. The tremendous variability in amplitudes is due to the radiation pattern of the source and, to a large extent, to site amplification. For example, instrument SOK01NA at almost twice the distance (23km) from the epicentre displays a five times larger peak acceleration amplitude than instrument PGC01NA (11 km). Attenuation functions based on an isotropic source model fail to predict this kind of variability.

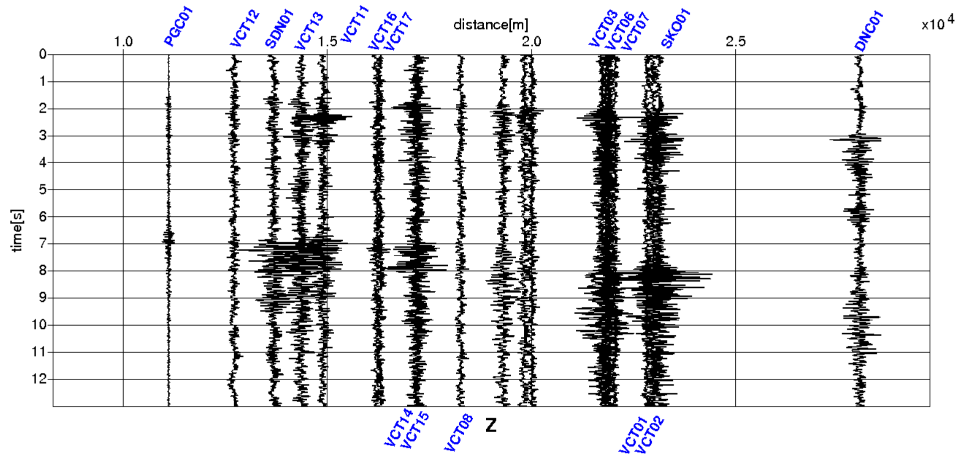

Figure 5. Vertical component data vs. epicentral distance from the January 15, 2006 event. Amplitude variability is due to radiation pattern and local site amplification.

Client Systems

The ground motion reports generated from a large number of instruments in this network need to be presented in a visualization which is suited for non-expert use. Based on the number of reporting stations and the strength of shaking reported, some additional tasks may have to be performed automatically. We currently operate two prototype systems which perform those tasks and which we refer to as clients of the network.

One system which continuously receives trigger messages and ground motion parameters is installed at the Geological Survey of Canada's Pacific Geoscience Centre in Sidney, BC. It consists of a simple PC running a program which parses incoming trigger-messages and either discards reports with small spectral intensity values or, if peak SI is over a certain threshold, adds the trigger data to a queue-like structure. Triggers already in the queue, which are 90 seconds older than the present one (with respect to their time stamps), are removed from the queue and finally the total count of triggers currently queued is taken. If the result is greater than a preset threshold (currently 5) the client system issues an alarm. In essence this very simple algorithm implements a very robust voting scheme: Within 90 seconds, the maximum time an S-wave would need to traverse the network in southwestern British Columbia, a minimum number of instruments need to vote that a sufficiently strong event has actually happened to set things in motion. The system then sends an e-mail to a mailing list with automatically generated maps attached which depict symbols of different size and colour depending on reported PGA and PSI at instrument locations. This client system will also automatically collect full waveform data from all instruments bracketing the event time.

A total of eleven instruments triggered and reported ground motion parameters during the small earthquake near Victoria on January 15, 2006. Only one (VCT03NA) reported a peak spectral intensity greater than the pre-set threshold of 0.4cm/sec^2 in Katayama (1988) units. Only this report was queued and since it was the only report in the queue over the next 90 seconds no alarm was issued, as would be expected for a small event like this. An additional ten instruments recorded the event but did not trigger.

A second client system was developed in co-operation with the Ministry of Transportation, British Columbia (MoT(BC)). In 2005, MoT(BC) initiated a specific program to instrument lifeline bridges and critical areas of high seismicity to provide measurements of ground shaking and record the response of the structures during earthquakes. The user interface of this second client system is shown in Figure 6. This interface is, to a large degree, platform independent. It can run on desktop computers with different operating systems and employs the same basic report queuing scheme but also displays triggers as they arrive on several GIS generated maps as circles with sizes varying with reported PGA and colour according to reported PSI. Symbols are removed from the map after 90 seconds unless more than a certain number of trigger messages arrived during this time interval. Then all symbols are retained and newly arriving ones are added to the map, until a user intervenes.

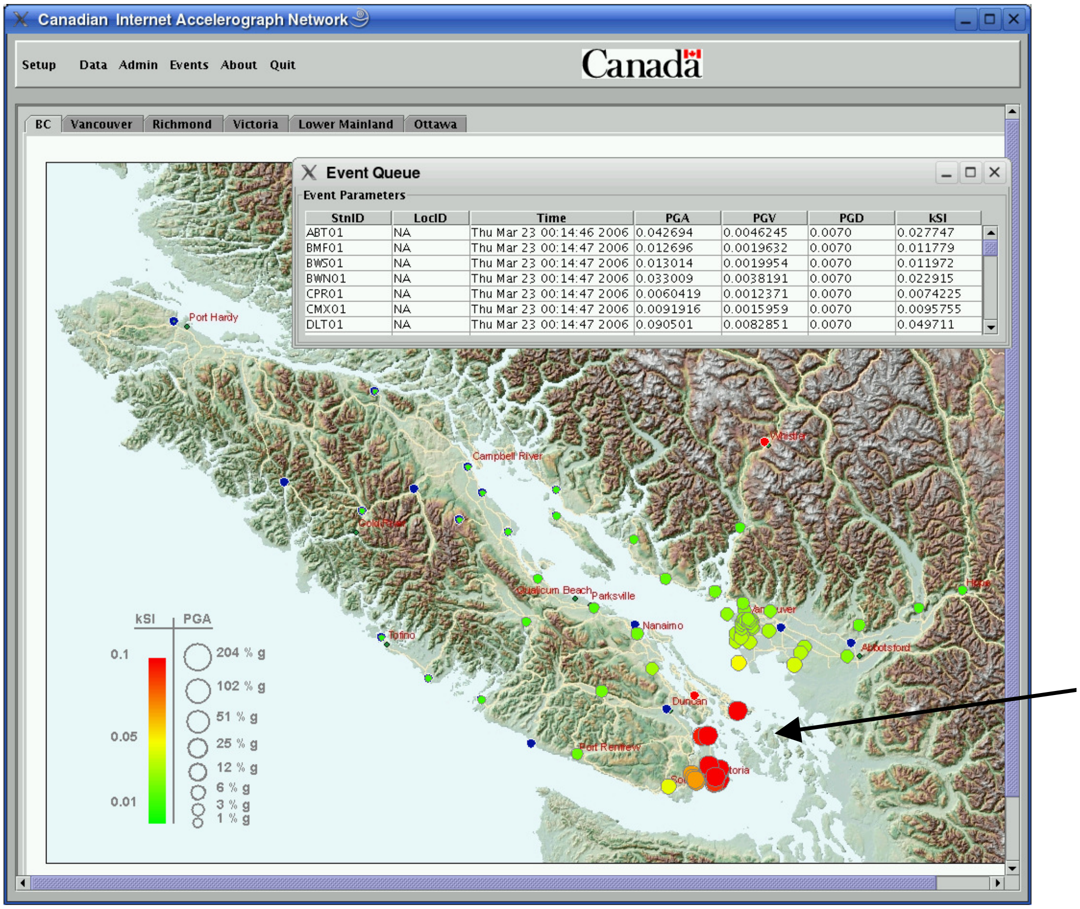

Figure 6. A desktop client developed jointly with the BC Ministry of Transportation. The map displays data from a simulated magnitude 6 earthquake 25 km northeast of Victoria on the present network (the arrow indicates the approximate epicentre). This map displays data in near-real-time and would be available before the earthquake has actually been located. Yellow to red indicates moderate to severe shaking. An additional window shows the queue of event reports. Maps of different scales can be selected. This interface can also be used to retrieve and view full wave-form data.

The map can be printed at any time and, in a significant earthquake, represents the first snapshot of ground-motions as they are recorded. The use of a GIS system to generate base maps opens the opportunity to tailor different thematic maps for emergency responders, life-line, and critical infrastructure operators. The MoT(BC) will be using these data to identify structures subject to the greatest potential damage following a significant earthquake. Because the map is GIS based, the Ministry will be able to overlay it with their bridge inventory, their Disaster Response Routes or other critical data sets needed for post-earthquake response.

Client systems can be set up using the same building blocks. For instance, an early warning system for approaching strong seismic waves could be set up. Such a system would use the first message transmitted from an instrument rather than waiting for ground motion parameters. The system would simply analyze the proximity in time of messages arriving from an array which is optimized to trigger on P-wave arrivals in a particular source scenario (e.g. Cascadia subduction earthquake) and issue an alarm when a certain number of triggers arrive within a time appropriate for the source/array geometry.

Conclusions

A new, real-time, low-cost, low-maintenance strong motion seismograph network of more than 100 instruments has been deployed in southwestern British Columbia since 2002. These instruments have been operating exceptionally well, and have demonstrated that an efficient strong motion network can function without an elaborate and sophisticated data centre.

The new GSC strong motion seismograph network utilizes an "all in one" low-cost (less than $2500) instrument comprising sensors, a digitizer, and a computer to handle signal processing, data storage and communications (via a continuous internet connection). When a trigger is detected at any site, peak values of acceleration (PGA), velocity (PGV), and spectral intensity (PSI) are computed and forwarded to clients. When more than 5 triggers are detected within 90 seconds across the network, automatically generated maps of ground shaking are also sent out via email.

This network is providing larger datasets of “weak” strong motion from modest earthquakes (typically 5-10 times larger) than those available in the past, which are useful for estimation of earthquake site effects and defining seismic attenuation. It also provides critical data for the generation of near-real-time ground shaking maps immediately after an earthquake. To date, the new strong motion network in southwest BC has made nearly 500 accelerogram recordings from six local and regional events with a magnitudes ranging from 3.4 to 6.4. Data from this new network can be obtained by contacting the authors at the Geological Survey of Canada.

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