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ENGINEERING APPLICATIONS OF REAL-TIME GROUND MOTION MONITORING

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ABSTRACT

Modern strong motion instrumentation with on-board computing capabilities can serve multiple purposes when connected in networks with fast Internet based telemetry.
Since the instruments can feed their data directly in to rapid response systems they contribute in an enfolding earthquake to immediate situation awareness long before results from conventional reconnaissance missions become available.
Their data can be integrated with structural monitoring systems to aide in the rapid assessment of critical infrastructure and life lines in the aftermath of a large earthquake.
They can also help to fill the often still sparse data-base of strong ground motions required for seismic engineering and hazard and risk assessment in general.
All three applications require a sufficiently high density of stations in a high earthquake risk area and as well a new type of smart instrument which can provide a parameter set describing the nature and severity of earthquake ground motion in real time and in a form suitable as input for engineering models.
A network of about one hundred novel instruments in British Columbia delivers parametric ground motion data directly to client systems in near real time without the de-tour through a seismic data centre. We give an overview of how the network operates and present examples from recent local earthquakes.

Introduction

Modern, compact, strong-motion seismographs have capabilities beyond basic data acquisition. They use small computers (embedded systems) to continuously compute a set of basic parameters from recorded ground motion and provide Internet connectivity to report parametric information, for example, peak ground acceleration, velocity, displacement and spectral intensity (Housner, 1952, Elenas, 2002, Katayama et. al., 1998) from an event in (near) real time (Rosenberger et al., 2006). The instruments record full waveform data in a ring-buffer of 36 hours capacity and transmit waveform data on demand. Data from detected events are also stored in non-volatile memory and can be requested from the instrument at a later time.

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An important advantage of this type of instrumentation is that it does not require the continuous transmission of digital waveform data to a seismic data centre. Signal detection and much signal analysis can be performed in real time on the instrument. Summary parametric information can then be delivered directly from the instrument to any generic control or rapid response system. This eliminates single points of failure, and saves time and communication bandwidth. The instruments can easily be organized into sub-networks and then perform in special contexts such as tsunami early warning. Event detections from a number of suitably positioned instruments can be used to rapidly determine if the epicentral region of an event is under water on a potentially tsunami-genic fault (cf. Rosenberger, 2009).

The Instrument Network

By the end of 2006 about one-hundred sites in south-west British Columbia, Canada, were instrumented. Due to a funding lapse and lack of maintenance about sixty remain in operation in 2009.

The communication bandwidth required by an instrument is extremely low in normal operation; on average less than 25 bits/sec since full waveform data are not routinely transmitted. This facilitates the use of a wide range of communications technologies. The GSC's instruments are hosted on third party Internet (including private, residential DSL/Cable), satellite, and cellular data 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 (cf. Figure 4). The use of a relay facilitates the communication with instruments that are on private networks which 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.

Currently two relay servers are used in our network. One relay is located outside the high seismic hazard area and serves as back-up systems in the event of a large earthquake affecting the coastal region. Both relays are additionally equipped with a GPS clock and provide time to most instruments via the network time protocol (NTP) service.

Real-time P-Wave Detection and Early Warning

Real-time signal processing on each individual instrument can reliably distinguish P- and S-waves, even with very noisy data (Rosenberger, 2010). The example in Figure 1 is from a small ML2.2 earthquake on July 6, 2009, 11:00 UT, southwest of Victoria, BC, Canada, recorded at a distance of about 30km with a strong-motion instrument of 50μg (≈ $5 mm/s^2$) sensitivity. Figure 1 shows the composite result of separating P and S arrivals. The instrument can detect P- and S- waves separately and report time-stamped parametric information about the P- arrival, such as peak amplitude and displacement directly to a subscribing control system with latencies less than 5 seconds.

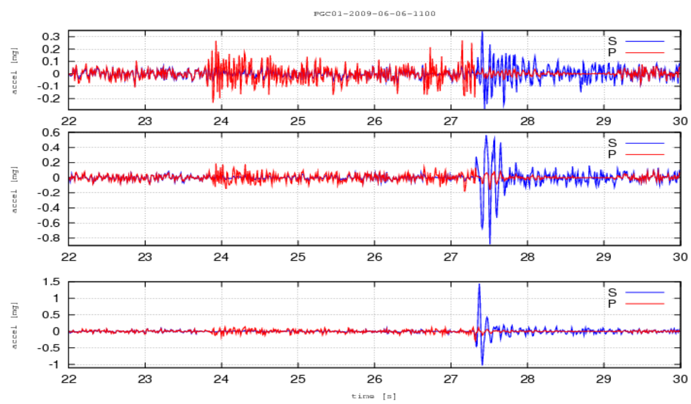

Figure 1. Discriminating P- (red) and S-Phases (blue) for separate detection.

A local, on-site (Kanamori, 2005) seismic supervisory control and data acquisition (SCADA) system as it would be used in a nuclear power-plant or a traffic control system (cf. Nakamura, 1988), can integrate detections from the regional monitoring system. Provided that an instrument or a group of instruments in the regional network is close to the epicentre of the event, the lead time, the time between the detection of a P-wave and the arrival of the potentially destructive S-wave at the site to be protected, almost doubles from an epicentral distance greater than about 50 km. The on-site control system can still apply its own thresholds to decide whether it should trigger an alarm or initiate mitigation measures.

Intensity Mapping for Rapid Response

S-wave parametric information, including spectral intensity measures, can be used to rapidly indicate and assess the extent of the affected area. The important point here is that measurements of ground motion, as opposed to mere estimates from attenuation curves, represent the effects of source radiation characteristics as well as local soil response. A reasonably dense network can provide the input data for damage and loss models (Erdik et al., 2003). Figure 2 shows an example of an intensity map for the simulation of a Mw 7.9 earthquake, 40km west of Victoria (British Columbia, Canada). Spectral intensity is colour coded outlining the southern tip of Vancouver Island and in particular the western communities of Victoria as the most affected areas. During a real event, this map, generated from real-time ground motion parameter reports, would be available in less than two minutes after the onset of shaking.

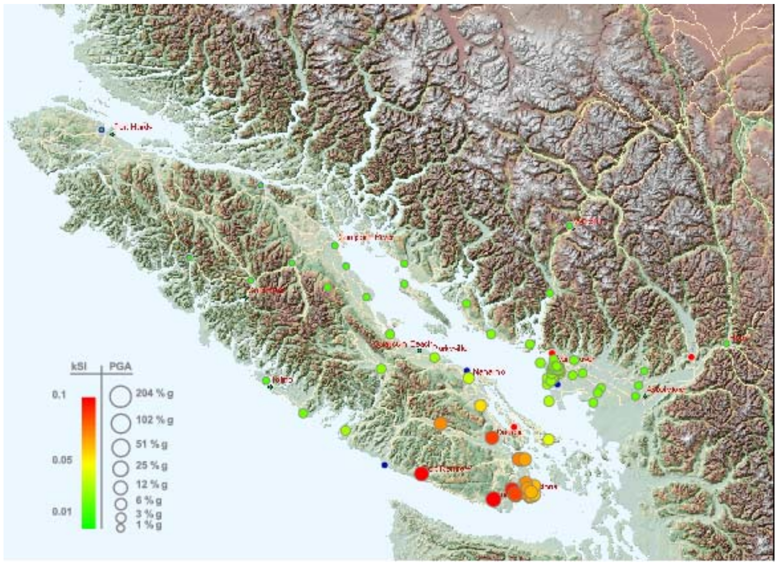

Figure 2. Spectral intensity measured at the instrument location is color-coded, PGA varies with symbol size.

Rapid Determination of Epicentral Area

Since each instrument's clock is synchronized to master clocks by means of the Network Time Protocol (NTP), time stamped signal detections from the respective seismic phase of an event can be used to establish an arrival order (cf. Anderson, 1981). The arrival order in turn constrains the epicentral region through simple geometrical relations and the geometrical problem can be solved in near real time by computation of a higher order Voronoi diagram (Rosenberger, 2009). The example in Figure 3 is from an under-water construction blast (1.374 t of explosives) on February 23, 2006. In essence, ordered arrivals from four stations are sufficient to constrain the source location to the central part of the Vancouver harbour. The actual blast location is close to the southern most vertex of the hatched polygon.

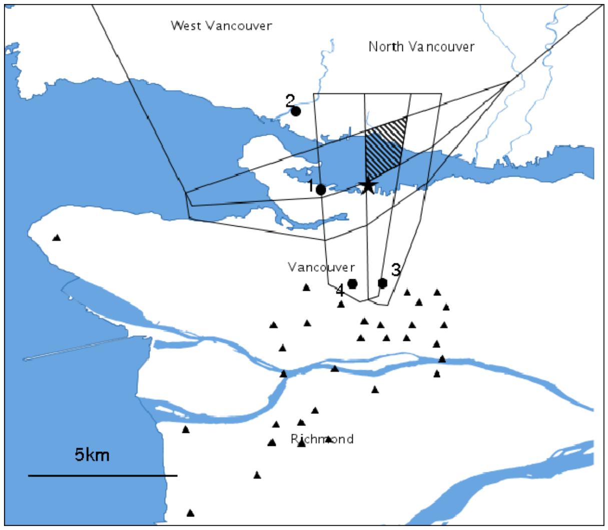

Figure 3. Epicentral region by arrival order location (AOL), four instruments detected a construction blast in the Vancouver (Canada) harbour (star indicates blast site).

In a tsunami early warning system (TEWS) information about the epicentral region would provide an answer to the first question in the decision logic: Did the earthquake occur under water?

Arrival time order location (AOL) does not require a seismic velocity model. Accurate instrument locations and an instrument capable of detecting and reporting seismic P- and S-phases with time stamps accurate to a few tens of milliseconds are the fundamental building blocks for a basic system. AOL like other location techniques will fail if detections from different seismic phases are mixed in the computations, the instrument's ability to identify the respective seismic phase is essential

Conclusions

A dense regional network of next generation strong motion instruments, capable of detecting and discriminating basic seismic phases can support on-site earthquake early warning (EEWS) or rapid response systems. Since the response thresholds for ground motions from S-phases would be much larger than for P-phases, parametric reports need to be labelled with the associated seismic phase. Modern strong motion instrumentation can detect P- and S-waves separately und thus provide separate sets of ground motion parameter reports to any subscriber system. The information flow for a hypothetical traffic control system is sketched in Figure 4.

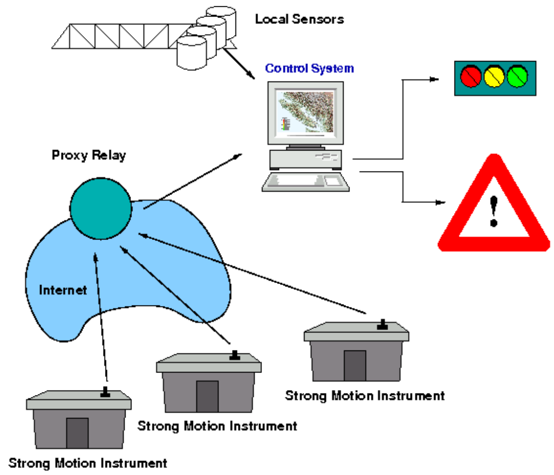

Figure 4. A regional network supporting an on-site traffic control system.

Phase detections will also facilitate the (near) real-time determination of the epicentral region and peak ground motions reported from a dense network of stations will delineate the most affected areas. Both types of information are crucial during the early stages of disaster response.

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