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National Earthquake Early Warning for Canada

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ABSTRACT

Natural Resources Canada (NRCan) is developing a national Earthquake Early Warning (EEW) system as part of the Canadian Emergency Management Strategy. NRCan's EEW system will complement the existing seismic network by adding over 300 accelerometers in western British Columbia, eastern Ontario, and southern Quebec. An additional 100 to 150 stations will be deployed by partner organizations in these regions. The EEW network covers the areas of highest seismic risk in southeastern and western Canada. The EEW system is slated to be operational by April 2024, and will provide alerts from a few seconds to tens of seconds before the onset of strong shaking.

EEW Alerts will provide the opportunity for individuals to take cover, and for automated engineering systems to initiate protective actions. Fault-tolerant systems, those with a low cost for action initiation but a high potential consequence for inaction (e.g., stopping trains), will benefit most from automated systems. Technical users will need to decide on their actionable thresholds, based on their priorities and tolerance levels. NRCan is simultaneously upgrading its prompt post-earthquake notification system which provides progressively updated information in the minutes immediately following an event. These notifications will provide more detailed event information, such as raw and processed ground motion intensities, and impact assessments for earthquakes within Canada.

The EEW sensors will provide many more strong motion recordings of significant earthquakes, helping researchers map the variation in ground motions in more detail. The records will better constrain the input shaking for forensic engineering, and will improve our understanding of strong earthquake shaking to advance seismic hazard estimates for the National Building Code. In this paper, we present NRCan's EEW system and upgrades to post-earthquake notification systems and discuss the potential opportunities for a range of stakeholders.

Keywords: Earthquake Early Warning, post-earthquake notification, earthquake risk mitigation, strong ground motion, earthquake alerts

INTRODUCTION

Canada has experienced damaging earthquakes in the past and further strong earthquakes will occur in the future. Offshore Haida Gwaii, British Columbia, the Queen Charlotte Fault zone has seismic gaps (areas between major rupture zones, where earthquakes are likely to occur within decades) and hosted Canada's largest instrumentally recorded earthquake, a M8.1 in 1949 [1,2]. Moreover, mega-thrust earthquakes are known to occur on the Cascadia Subduction Zone (CSZ), where the largest earthquake to impact Canada occurred with an estimated M9.0 in 1700 [1,2]. The compression along the CSZ also causes strong (M>7) earthquakes to occur within the adjacent plates. In eastern Canada, large earthquakes have occurred within the Charlevoix Seismic Zone in 1663, 1791, 1860, 1870, and 1925, with estimated magnitudes of M7.0, M6.0, M6.0, M6.5 and M6.2, respectively [2]. In 1989 a M5.9 earthquake occurred near Saguenay, Quebec [1,2], an area without known prior seismic activity; it caused damage to the Montreal-East city hall, some 350 km away.

Despite improving building code requirements for new construction, a significant proportion of Canada's building stock was constructed before seismic provisions within the national, provincial, and municipal building codes were at modern standards for seismic safety, e.g., approximately one third (34%) of all buildings in Metro Vancouver were constructed prior to the mid-1970's [3]. Additionally, the constant growth of population and an aging infrastructure has increased the possibility of significant damage from an earthquake [4]. In 2013, the Insurance Bureau of Canada estimated two significant, but reasonably expected, earthquakes in western and eastern Canada would cause losses of $75 billion and $60 billion, respectively [5].

Natural Resources Canada (NRCan), the federal department responsible for the provision of authoritative information about earthquakes in Canada, has been monitoring seismicity in Canada for over 125 years [1]. Digital monitoring using the Canadian National Seismograph Network (CNSN) [6,7], shown in Figure 1, can detect all earthquakes of M4+ in or near Canada, and smaller, potentially felt, earthquakes in areas with higher rates of seismicity. Last year, seismic analysts located and classified more than 7400 seismic events, including earthquakes, blasts, and mining or industry-related events [8], as shown in Figure 2.

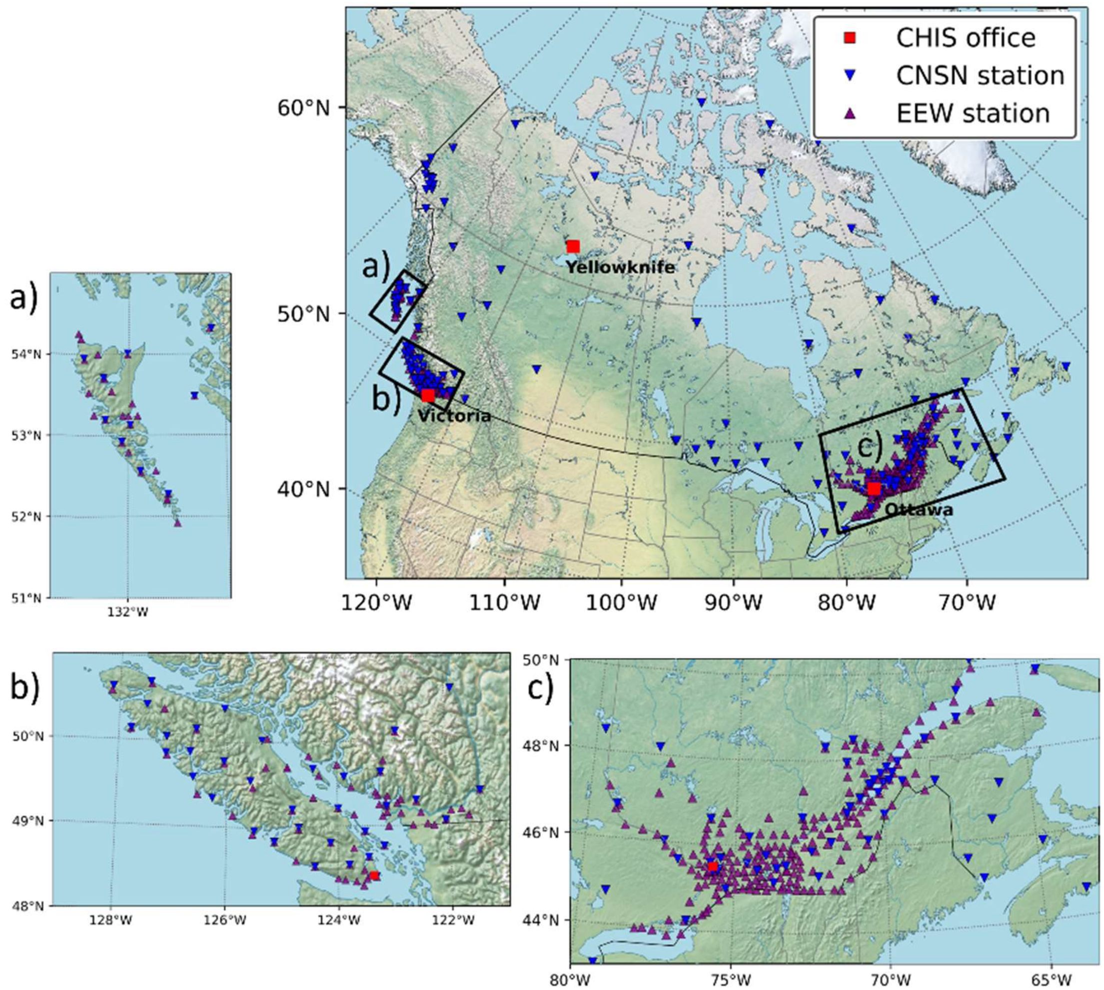

Figure 1: The Canadian National Seismograph Network (CNSN) and the planned Earthquake Early Warning (EEW) network, with maps of a) Haida Gwaii, b) southwestern British Columbia and c) eastern Ontario and southern Quebec.

The primary protection against damage to infrastructure is the implementation and enforcement of seismic provisions in the National Building Code of Canada (NBCC) [9]. These provisions have undergone several updates as our knowledge and understanding of seismic sources, and the impacts of earthquake shaking have advanced. The current seismic provisions in the 2020 edition of the NBCC use the 6th Generation Seismic Hazard Model of Canada [10] as the basis for seismic design values. Code updates chiefly modify the level of seismic protection required for new buildings, whereas older buildings or infrastructure remain at a lower level of earthquake resistance.

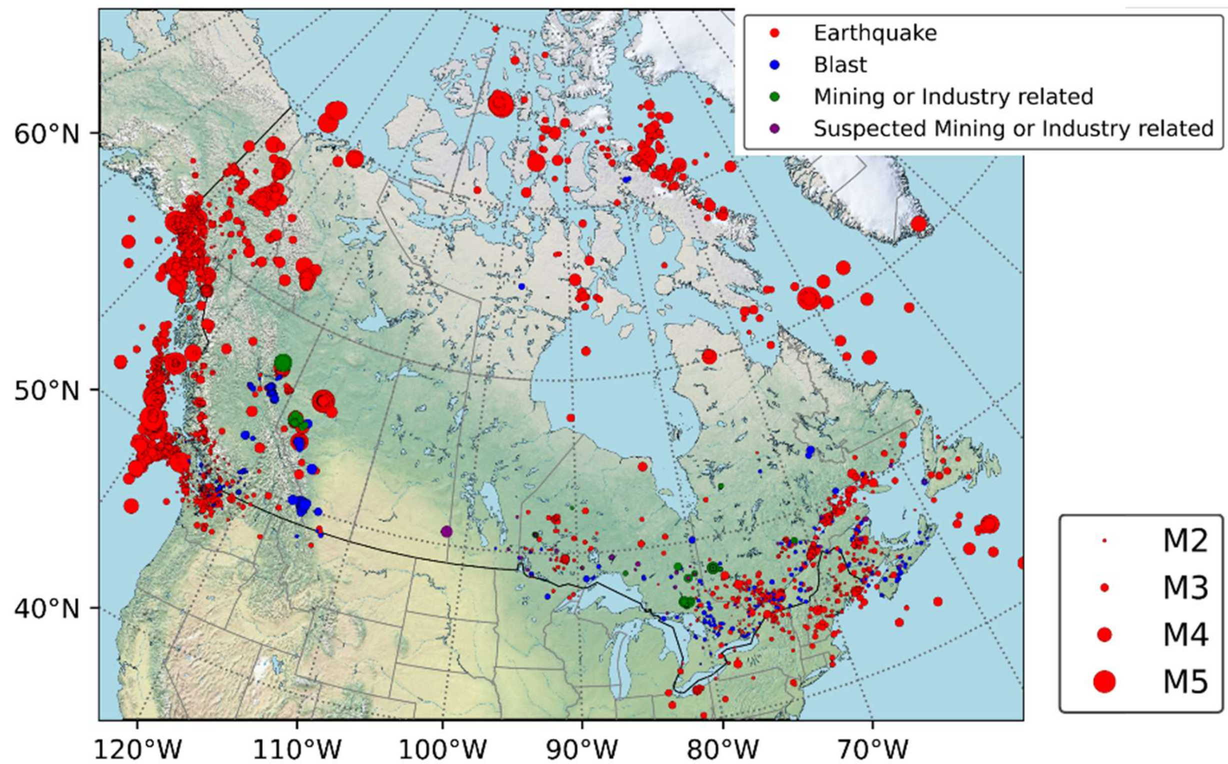

Figure 2: The seismic events during the year 2022 as located and classified by Natural Resources Canada. Note these may be preliminary and subject to further updates.

Earthquake Early Warning (EEW) is an emerging technology, which mitigates the negative impacts caused by earthquake shaking by permitting protective actions to be taken seconds before the strongest shaking occurs. These actions could be as simple as stopping trains to reduce the risk of derailment, stopping elevators at the next floor and opening the doors, or allowing doctors to pause surgical procedures. Taking such actions before the arrival of strong ground motions could prevent disastrous outcomes (including injuries and fatalities) and enable first responder resources in the immediate aftermath of an earthquake, potentially reducing the recovery time.

EARTHQUAKE EARLY WARNING

Background

Earthquake Early Warning (EEW) systems are designed to rapidly detect and characterize earthquake sources, then estimate the expected ground motions to provide advance warning of incoming strong shaking (Figure 3). These systems could provide seconds to tens of seconds of notification prior to the arrival of potentially-damaging shaking. EEW systems are currently in production or in development worldwide in several countries or regions of elevated seismic hazard including Japan, Turkey, China, Taiwan, Mexico, the west coast of the United States, Israel, and several other regions [11].

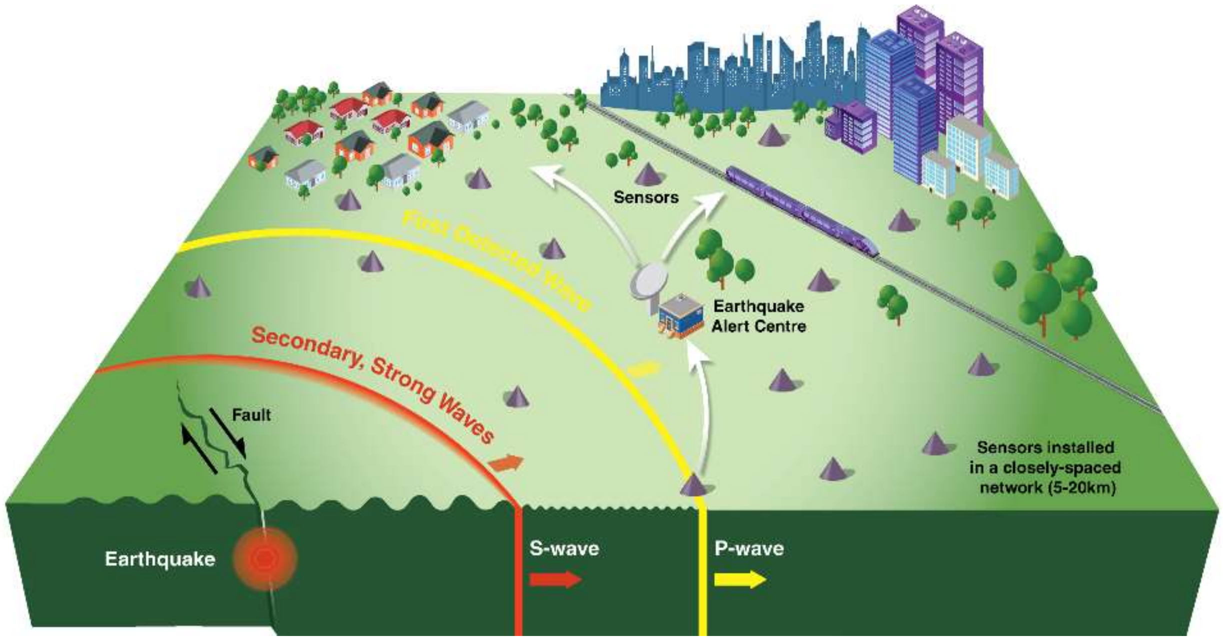

Figure 3: An illustration of how an EEW system works.

EEW functions by detecting the faster and smaller amplitude (weaker) P-waves from an earthquake, determining its source parameters, and then using those to estimate the arrival of the slower but larger-amplitude (stronger and, generally, more damaging) S-waves. The current EEW system requires a detection of an earthquake at a minimum of four stations to have enough confidence that the signal being detected is an earthquake and not coincidental noise. The average velocity of the crustal P-waves in Canada is about 6 km/s, so having four stations within 20 km of an earthquake, which is the design spacing of the EEW network, should result in an earthquake detection within 8 seconds after accounting for data and processing latencies [12]. By disseminating the alert with a latency of less than one second or two, facilities and the public as close as 50 km to the epicentre would be expected to receive 5 seconds of warning time. This example is purely illustrative, and actual warning times will depend on sensor distribution around the earthquake epicentre, the earthquake depth, and the latencies of the data transmission and processing at the data centre [12].

An important limitation regarding EEW systems arises from the fact that an earthquake must begin rupturing before the system can detect the earthquake. This means those closest to the earthquake epicentre and the most likely to experience the strongest shaking may not receive a timely alert. The “late alert” zone, close to earthquake’s epicentre, is where the alert arrives after the strong shaking (S-waves). Since the strongest shaking produced by an earthquake occurs near the earthquake source and then shaking levels decrease as you move away from the earthquake, the areas that receive the strongest shaking will also receive the least amount of warning time [13-15]. Due to this limitation, those who have a low cost of taking automated actions but a high cost of failure will benefit the most from EEW [14, 15]. Also, the farther people are from an earthquake the more warning time they will generally receive.

EEW Network

The EEW sensors, map view in Figure 1, are being deployed in areas of high and moderate seismic risk including western British Columbia, eastern Ontario and southern Quebec. Partner organisations will supplement this network with additional sensor stations in and near these regions, providing increased coverage for their specific needs and additional redundancy to the network. The sensors are Nanometrics TitanSMAs and Güralp Fortimus strong motion accelerographs. Three generic station designs have been created to accommodate the common environments for sensor locations, the requirements for rapid communications and resilient operations, and to ease rapid deployment and installation of many stations in a short timeframe. Typical station designs are shown in Figure 4.

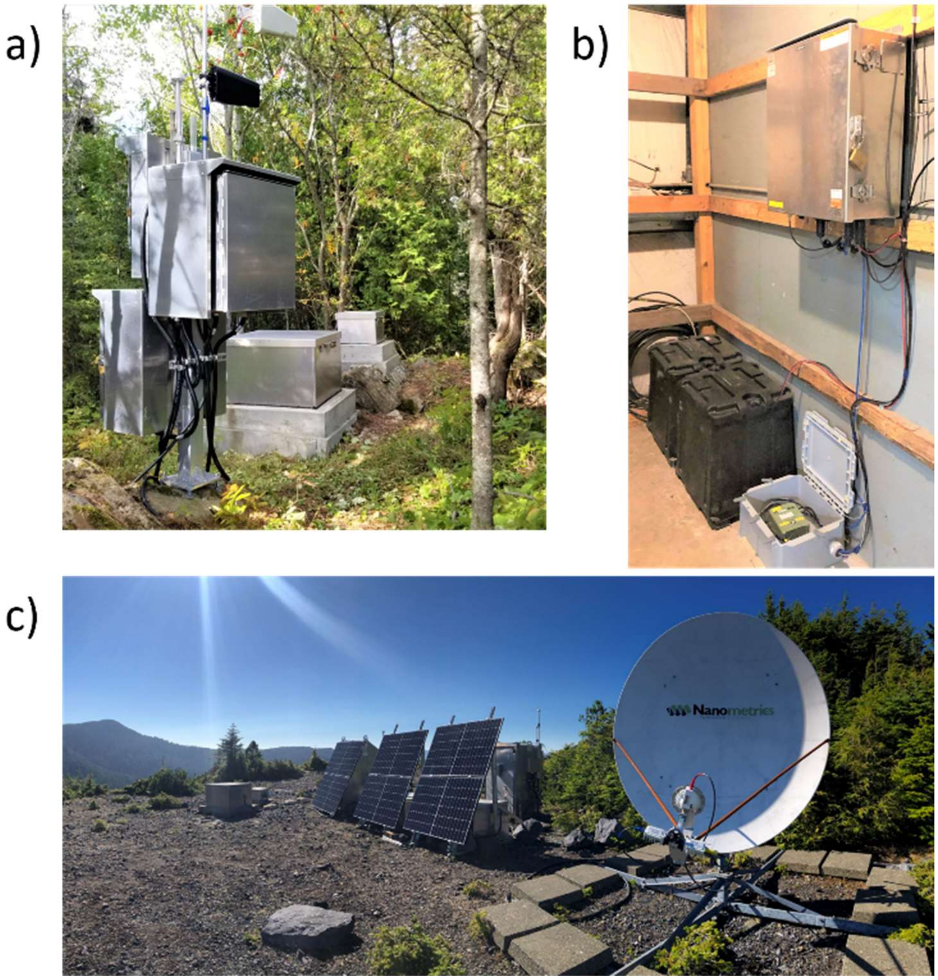

Figure 4: Typical station installation for a) outdoor with AC power, b) indoor, and c) remote sites.

The sensor deployment for EEW has a somewhat different target layout than for routine seismic operations. For EEW, sensors should be densely sited in areas where earthquakes may occur, and preferably placed between earthquake sources and the areas needing an alert. Therefore, a target spacing of 10-20 km was used near important sites within earthquake zones, but less dense (20-50 km) where the earthquake sources are distant from the alerting areas. These target distributions are consistent with other studies on EEW networks [16]; an even denser spacing does not give significantly faster alerts. Many sensors are also situated in highly populated locations that are noisy, such as in basements. This is acceptable as the signal from an earthquake large enough to provide a warning will be larger than the cultural noise in these locations.

The addition of these sensors in densely populated regions or areas of seismic activity will provide valuable recordings of ground motions at close distances to earthquakes and allow for a better spatial mapping of the propagating strength of seismic waves. Recordings from within structures will provide site-specific ground motions, facilitating forensic engineering regarding structural response. Moreover, mapping the variability of ground motion on small spatial scales will allow for detailed understanding of site effects, leading to improvements to the seismic hazard estimates in the National Building Code of Canada [9].

Protective Actions

There are many possible protective actions that the public and industries can take, with several suggestions illustrated in Figure 5. The primary public response is generally to Drop, Cover, and Hold On (DCHO) to reduce the possibility of injury when appropriate. Other personal protective actions should be taken as the situation requires, such as safely pulling over and stopping your car if driving. Communication materials provided for the public, including vulnerable communities, are available through ShakeOutBC [17]; they outline a wide range of personal protective actions to be taken in a variety of situations.

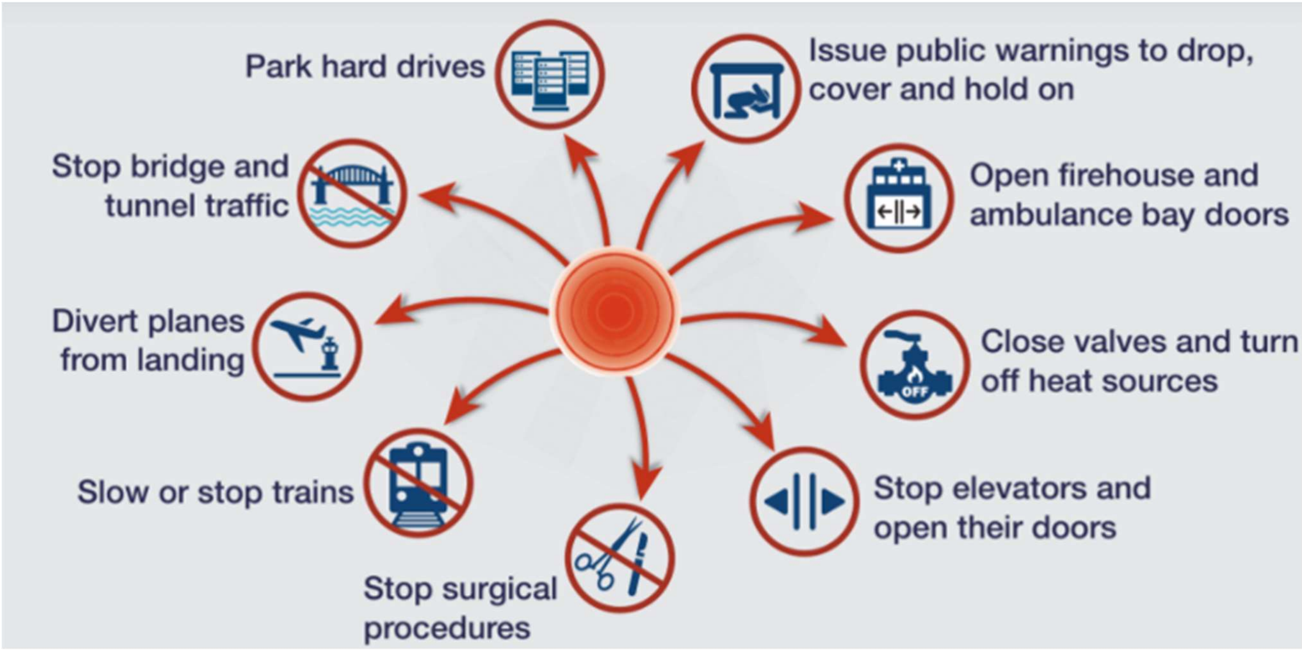

Figure 5: Possible response actions to take after receiving an EEW alert.

Proven protective actions taken by industries include securing hazardous chemicals and stopping sensitive equipment, which have been shown to reduce the cost of damage and shorten recovery time for a business [18]. For example, stopping elevators and opening their doors at the nearest floor was shown to be valuable for prevented people from being trapped and allowed first responders to devote time to others in need in Japan [18]. Similarly, slowing and stopping trains reduces their risk of derailment, potentially saving lives [18]. Technical users will be those that receive the alert directly from NRCan in order to trigger automated protective actions.

The actions taken by various technical users will depend on the possible automation of safety actions. Technical users will be able to subscribe to EEW messages (in XML format) to determine if predefined thresholds are expected to be exceeded and therefore actions are required. Since ground motion estimation is difficult and highly variable, these technical users should build in safety factors based on probabilistic assessments of ground motion exceedance [19]. Being able to take low-cost actions at lower shaking thresholds in order to prevent costly failures will have the greatest return on investment for technical users of EEW [14,15].

EEW Software

The USGS Earthquake Early Warning software suite [20] is provided by the United States Geological Survey (USGS) and will be used collaboratively with data sharing to ensure consistent cross-border alerts. The software consists of several modules including a point source detection algorithm [EPIC, 21], a finite fault template matching algorithm [FinDer, 22], a solution aggregator to combine results from the point source and finite fault detections, and an algorithm to estimate ground intensities [eqinfo2GM, 23]. The results from these algorithms are sent though different decision modules before providing either public or technical user alerts. The modular design of this software suite allows for the possible addition of future EEW algorithms, for example, a ground motion forward predicting algorithm [PLUM, 24] or addition of GNSS data to enable rapid estimation of magnitudes for especially large events [GFAST, 25]. Using software that has already been proven successful for EEW [20] will provide confidence in the overall system and ensure reliable alerting when the Canadian system becomes operational in 2024.

EARTHQUAKE RESPONSE PRODUCTS

Concurrent to building an EEW system, NRCan is also currently modernizing its suite of post-earthquake products [26]. A conceptual framework for the earthquake rapid alerting products is shown in Figure 6, where the first available products will be a result of the EEW system (in yellow), followed by prompt notification products that will follow in the minutes after an earthquake (in orange). These prompt notification products, several of which are already available, include ground motion data recorded by the sensor network through an FDSN web-service, processed data including recorded peak ground motions and spectral accelerations, a ShakeMap [27] of interpolated shaking intensities, asset impact forecasts, and a regional impact assessment.

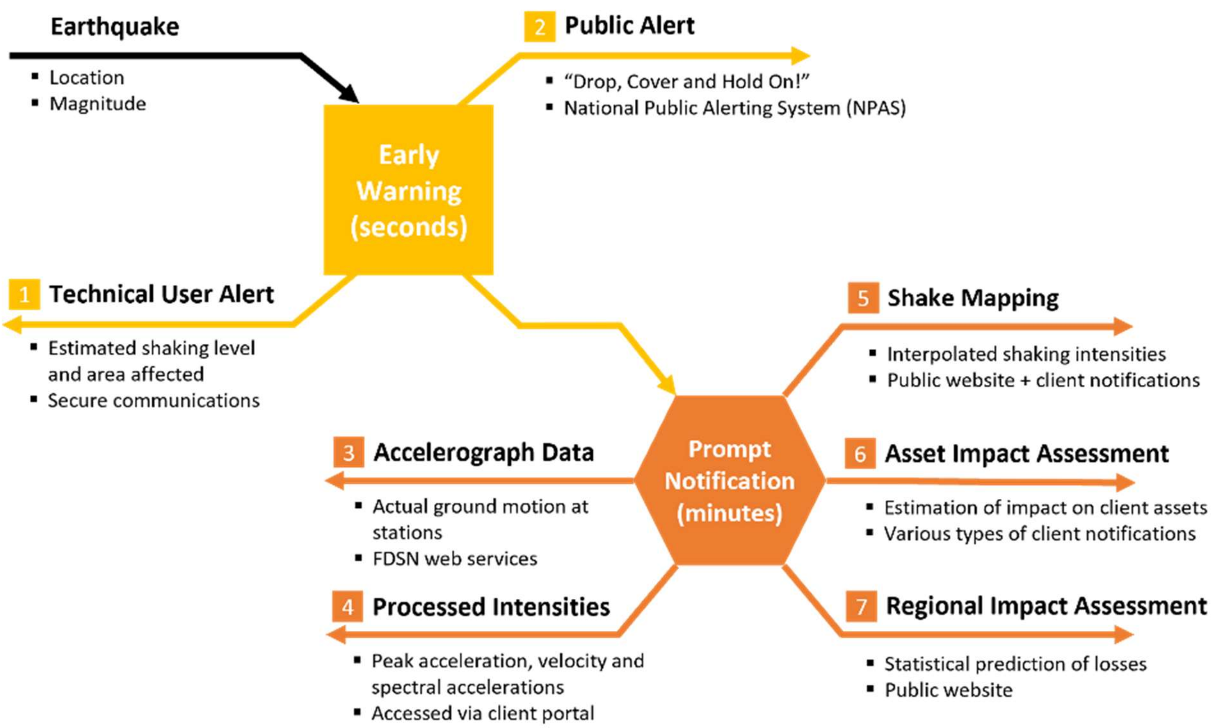

Figure 6: Conceptual framework of the suite of post-earthquake products NRCan is aiming to provide. The numbering roughly indicates the complexity of a product and passage of time until that product will be available.

NRCan is responsible for providing authoritative public information on significant seismic events in or near Canada. Significant seismic events are typically defined as events of M4 or greater, events that are widely felt, or an event expected to generate significant public interest. Using a combination of automated and manual processes, event information for significant events is rapidly posted to the Earthquakes Canada website [26]. Although this information is timely and available 24/7, it is not designed for rapid response or critical business operations. Prompt notifications for critical business operations have been available through NRCan's prompt notification service since 1998. These are widely subscribed to by different types of clients across Canada such as government and private organizations, including critical infrastructure (CI) operators.

Instrumental Recordings of Ground Motions

Recordings of ground motion from the sensors, along with the metadata of the station information from the CNSN and EEW networks, will be available through an FDSN web service [28]. These recordings are often available with minimal latencies, on the order of several seconds. Latencies may become longer with an increase in traffic to the web service, as is likely to occur after a significant earthquake. These recorded ground motions will help seismologists and engineers complete initial damage assessments and, later, provide input to research, such as earthquake source parameter determination.

Processed Ground Motions

Although instrumental recordings of ground motions will be readily available, processed data is not as trivial to generate for non-experts. As such, automated routines will process seismic data after a significant earthquake to provide useful parameters, such as peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration (SA) at different periods, to engineers and other interested clients. This data will be retrievable by the clients through a client portal shortly after an earthquake.

ShakeMaps

ShakeMaps are visual representations of interpolated ground motions based on recorded seismic data and reported intensities [27]. These maps are useful for providing a spatial overview of the estimated ground motions resulting from an earthquake. It often takes minutes for the first of these maps to be generated, and it can be hours to days before all data is collected and then incorporated into these maps. The maps will be made available to the public through the Earthquakes Canada website. ShakeMaps can be used, for example, by emergency managers to prioritize initial reconnaissance into areas which experienced the strongest shaking levels after a damaging earthquake.

Asset Impact Assessment

Clients will be able to receive post-earthquake information for their assets to initiate various levels of response; some have been receiving these since 1998 [23]. Currently, these assessments require the client to provide simple, predefined thresholds and actions when those thresholds are exceeded. These thresholds could be simple magnitude-distance requirements or (better) exceedances of estimated ground motions at their assets. An example of a possible ground motion exceedance threshold for warning and action is shown in Table 1, adapted from [29].

Table 1: An example of possible ground motion thresholds and the associated response actions.

PGA (%g)	Classification	Action
≥ 10.0	Strong shaking	Protocol A
5.0 to 10.0	Moderate shaking	Protocol B
2.5 to 5.0	Weak shaking	Protocol C
1.25 to 2.5	Minimal shaking	Protocol D
< 1.25*	No Impact	None needed

*For M4+ and within 400 km

The final category ("No Impact") is included to reassure the client that no action is necessary, and to prevent an operator from taking unnecessary and possibly costly measures, as the earthquake may have been large enough to be felt – causing concern - but it may not have produced harmful shaking. Clients will often include actionable information within their own Protocols, to ensure a timely and appropriate response.

Updates to these products may include the possibility of clients adding fragility curves, or using generic ones, to complete a probabilistic asset impact assessment. The convolution of spectral acceleration and fragility curves can provide a statistical likelihood of the level of damage to an asset. Although this is more complex than the simple predefined thresholds for response, it allows clients to prioritize asset inspection when there are multiple assets under consideration [26].

Regional Impact Assessment

A regional impact assessment will combine the distribution of ground shaking, fragility curves, and a regional exposure database to estimate the overall damage and possible range of fatalities an earthquake might have produced. This may incorporate the current earthquake risk assessments and risk modelling performed by the National Earthquake Risk Assessment program [4]. The aim of the regional impact assessment product is to provide a rapid probabilistic assessment of overall earthquake impact to guide emergency response.

CONCLUSIONS

The national EEW system being developed by NRCan will provide timely warnings for the public and other recipients to take proactive actions before the strong shaking from a large earthquake arrives. This state-of-the-art system will benefit Canadians by allowing automated procedures to be activated, potentially protecting assets and reducing business recovery time, along with reducing injuries and fatalities by alerting people to protect themselves. Such EEW systems have been proven successful in other countries with significant earthquake activity. A collaboration, including data sharing, between Canada and the U.S. ensures consistent cross-border alerting.

NRCan is also updating and augmenting its earthquake rapid alerting products to advance the useful tools available for response after a large earthquake. The suite of products is aimed at providing various organizations, governments, emergency managers, and the public with the necessary information for appropriate and timely earthquake response operations. Adding to the current prompt post-earthquake notifications will also provide clients with more information to provide a better opportunity for making appropriate decisions for their post-earthquake response.

EEW alerts and the updated rapid earthquake alerting products will not replace the need for proper construction (to building code standards), preparation, and planning for earthquakes, but will help in the mitigation of risk and enable faster recovery after a damaging earthquake. Preventing earthquake impacts by taking necessary precautions is the best way to minimize the recovery time. The addition of a new suite of products by NRCan will help provide valuable information to those who require it to make the appropriate decisions for earthquake response and recovery operations.

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