CANADA'S AUTOMATED EARTHQUAKE NOTIFICATION SERVICE

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ABSTRACT :

The Geological Survey of Canada (GSC) provides automatic notification of significant earthquakes to agencies who need to respond rapidly. Currently railway operators across Canada, dam operators in Ontario, New Brunswick and Quebec, and nuclear power plant operators use this service ("ANHAS"). GSC uses its own 120-seismograph network plus data from another 90 seismographs in Canada and the U.S. Automatic earthquake location software (AUTOLOC) provides magnitude and location estimates, usually within 5-10 minutes of an earthquake, and GSC uses three independent sources of real-time AUTOLOC information for reliability. The notifications contain the basic earthquake information as well as response actions pre-defined for each client's facility and are transmitted by a variety of secure telecommunication means. Railway operators have standardized on the response: above 2%g - stop trains; 1.25-2%g - trains proceed at restricted speed; <0.6%g - no action needed. Most dam operators use response schemes based on *ad hoc* combinations of earthquake magnitude and its distance from each facility. Such schemes are not optimal, and have inherent flaws. A more reliable way would be to (i) estimate the peak ground acceleration at each site using the ground motion relations of the National Building Code, (ii) classify the shaking level according to the consequence, and (iii) base the response on the shaking classification level and the consequence of damage at the facility. The GSC encourages the development of such best-practice earthquake-response schemes.

KEYWORDS: Earthquakes, alert systems, infrastructure, dams, railways

1. INTRODUCTION

The Geological Survey of Canada (GSC) provides an automated rapid earthquake notification service (called ANHAS) for agencies in Canada that need to respond quickly to significant earthquakes. This service is now widely used in the Canadian railway industry. As well, some dam operators in Ontario, New Brunswick and Quebec use the service to prioritize and initiate dam inspections after strong earthquakes.

The GSC operates a national network of more than 120 continuous online seismograph stations that record earthquake activity in all parts of Canada, and accesses data from 90 other independently-operated stations in Canada and yet others in the adjacent U.S to supplement its coverage. These data are used by an automatic earthquake location program (AUTOLOC) that provides location and magnitude of earthquakes in near-real-time, usually within 5-10 minutes of the occurrence of the earthquake. AUTOLOC solutions are reviewed and revised by GSC's analysts and the earthquake solutions are added to the national earthquake database (Figure 1).

ANHAS continuously screens AUTOLOC activity 24 hours per day, 7 days per week for high-quality events, keeps track of the location of any of the earthquakes it selects, and applies the appropriate attenuation relationship to estimate the ground motion effects in each case. ANHAS notifications are issued to clients affected by a significant earthquake automatically via secure telecommunication procedures (ssh, sftp), where feasible, or by email or facsimile otherwise. In addition, pager or cell phone alerts can be delivered to individual personnel to alert them quickly that an earthquake has occurred. The procedures can be customized for each client but always include a set of pre-defined response actions for each facility close to the earthquake as well as the basic information about the earthquake. Each client's notification criteria usually include a 'near-miss' category which identifies earthquakes strong enough to be felt, but too weak to cause real problems. This avoids over-reaction by the operators, develops operator familiarity, and provides a useful validation of the operation of the notification/response system. 'Near-miss' events are actually much more common than earthquakes causing real damage.

Since its inception in 1998, ANHAS has been providing notifications for four railways with more than 55,000 km of track, and three hydroelectric companies with 485 hydroelectric and 4 nuclear power facilities. ANHAS is a best-effort, no-fault contract service and there is an annual fee charged to those companies who receive the service. ANHAS is not offered to individuals.

2. SEISMOGRAPH NETWORKS

2.1 GSC Network

The Geological Survey of Canada (GSC) operates the primary network of over 120 high-gain seismographs, and over 120 low-gain or strong motion accelerographs, that together make up the Canadian National Seismograph Network (http://earthquakescanada.nrcan.gc.ca/stnsdata/index_e.php). The high-gain instruments are used to record weak ground motion from distant sites and small earthquakes. The low-gain accelerographs are used to record the strong ground shaking at nearby sites from larger earthquakes likely to cause damage. For increased reliability, the continuous data streams from the seismograph network are acquired and analysed in near-real-time at two GSC offices, one in Ottawa and the other near Victoria. At the moment, the strong motion data does not feed into the automated system, but it is intended to add it in the near future.

2.2 Other Cooperating Networks

POLARIS (http://www.polarisnet.ca) is a Canadian geophysical research consortium focused on investigation of structure and dynamics of the Earth's lithosphere and the prediction of earthquake ground motion. It received research funding to install satellite-telemetry arrays of portable geophysical observatories in Canada. The real-time POLARIS network currently consists of about 75 seismographs which provide data via satellite or the internet that is forwarded to the GSC for archiving and dissemination, and is used for AUTOLOC processing.

The Advanced National Seismograph Network (ANSS http://earthquake.usgs.gov/research/monitoring/anss/) stations in the United States are very important for improving the accuracy of automatic locations for earthquakes that occur just outside Canada but close enough to cause possible damage. Real-time data streams from selected seismographs near the Canada-US border are exchanged cooperatively with the USGS. Selected data from both the POLARIS and ANSS networks are merged in real time by the GSC, and analysed together with the data from the CNSN network. Figure 2 is a map of the stations available to ANHAS.

3. AUTOLOC

Unlike some countries with more resources and/or greater earthquake hazard, Canada does not staff a continuous, 24/7 seismology centre. Instead, outside office hours two staff seismologists (one in Ottawa, and one near Victoria) are on 24-hour call by cell phone, and the GSC has spent considerable effort in the past decade creating automated systems to provide itself with rapid initial information about strong earthquakes.

The GSC developed its AUTOLOC program to quickly process the data streams from the seismograph networks and locate earthquakes automatically. AUTOLOC starts with a refined detection list (*rdl's*) for each station written by the CNSN detector; then requests waveform segments for time periods selected from the *rdl's* to evaluate each of the raw detections. Most of the detections are rejected as being noise, but groups of detections with larger amplitudes and longer durations, at geographically proximate stations, are selected for further processing. The AUTOLOC process runs the location program directly on the times from the *rdl's,* and then finds improved locations by 3-component processing of the waveforms to refine the phase onset times. The entire process takes a few minutes to locate events.

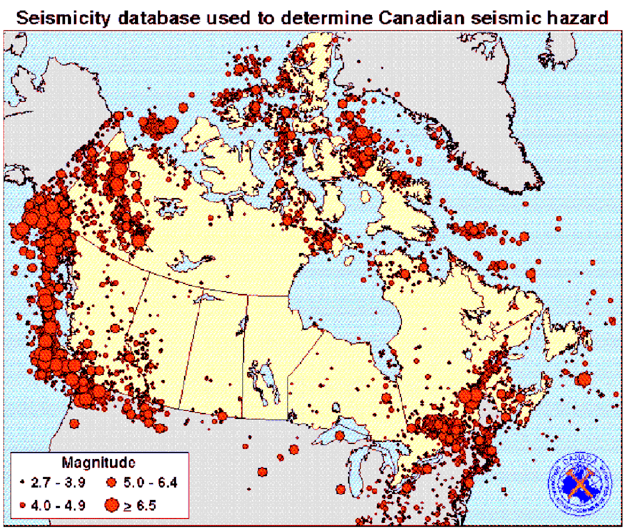

Figure 1: Seismicity map of Canada.

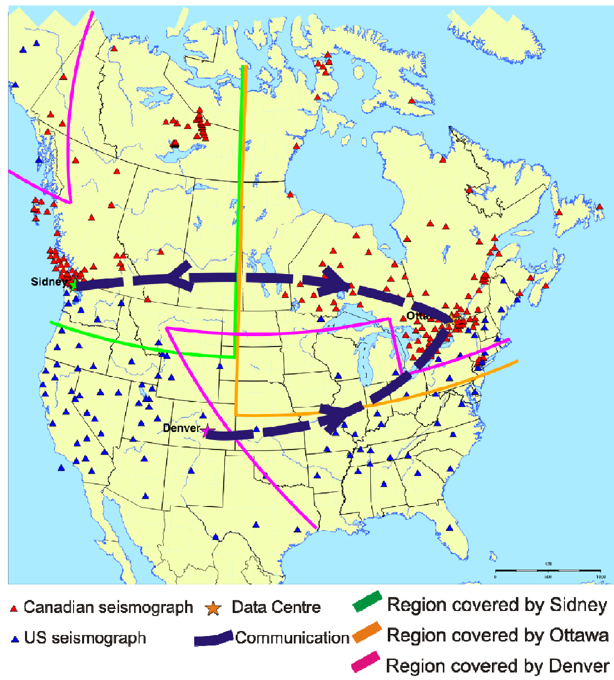

Figure 2: Map of the seismograph stations available to ANHAS, the inter-centre data flow and the regions for which the datacentre is considered a valid source.

When it has located a seismic event, AUTOLOC sends email messages containing the earthquake coordinates and magnitude, together with quality and other detection parameters, to the GSC personnel on call, and to other automatic programs such as ANHAS. AUTOLOC is currently sending the emails within 5 to 10 minutes of their occurrence (Fig. 3). Some of this delay is irreducible (the time taken for the seismic waves to propagate to the seismographs, for example), but the rest of the delay is slowly being reduced by using faster computers and smarter algorithms.

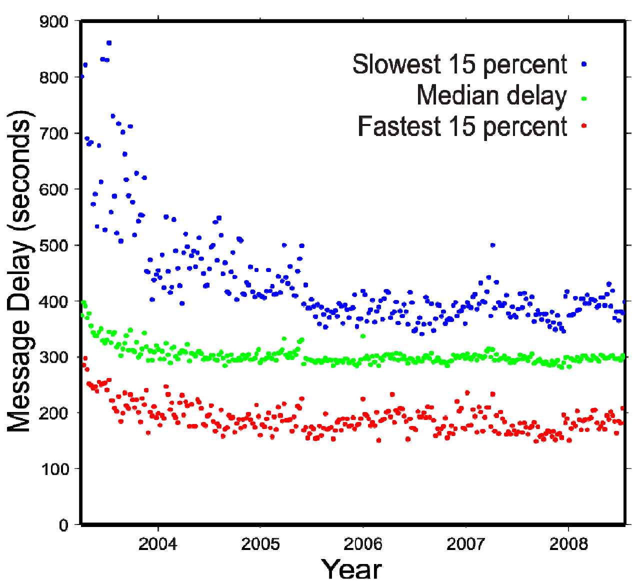

Figure 3: Weekly statistics for the delay between an earthquake and the AUTOLOC message. The median time delay has remained relatively constant despite increased complexities in the AUTOLOC system and the use of more stations for locations. The time delay for the slowest notifications (85th percentile) has dropped significantly (more than 40%) over the past 5 years.

4. ANHAS

GSC created the ANHAS automatic earthquake notification service to manage the information produced by AUTOLOC and forward it to industrial clients. ANHAS provides the rapid information about strong earthquakes that the clients need in order to respond effectively and efficiently when such an earthquake disrupts their operations. Clients have primarily been large transportation companies (Canadian National, Canadian Pacific Railway) and provincial power utilities (Ontario Power Generation, Hydro-Quebec, New Brunswick Power). ANHAS messages are transmitted automatically to these clients, usually within 5-10 minutes of the earthquake. Each message tells the client which of their facilities is most likely to be at risk because of the earthquake and suggests the (pre-decided) prudent response actions (see below).

Wherever possible, GSC uses secure telecommunication means to transmit ANHAS messages involving secure shell protocols (ssh), but it can also provide email or facsimile messages and cell phone or pager alerts following earthquakes as required. In fact, when dealing with emergency response information, it is advisable to deliver the message by a variety of channels to ensure its successful delivery.

ANHAS relies on an AUTOLOC system running at the GSC's Ottawa office as the primary source of information about earthquakes but maintains a duplicate system running at its office (Pacific Geoscience Centre) near Victoria to provide additional reliability. As discussed above, selected data from the GSC, POLARIS and U.S. seismograph networks are delivered in real time to both systems; either system can provide rapid information for earthquakes in all parts of Canada. In addition, GSC has developed online access to the autoloc-like system run by the US Geological Survey in Denver, Colorado, which uses seismic data from the entire ANSS. In this way, standard ANHAS notifications based on data from the USGS Denver operation can be produced seamlessly for clients with facilities located in the U.S. For example, the ANHAS system covers the extensive operations of Canadian rail companies in the U.S. which operate trains as far south as New Orleans.

ANHAS is an automated system that will react to a strong earthquake quickly. One of its primary functions is to screen out false alarms from the AUTOLOC systems. It does this by carefully considering the amount of data that is used for each AUTOLOC event. For the most part it can provide reasonably accurate information about *bona fide* earthquakes within a few minutes. However, the GSC continuously monitors the operation of the system and will issue updates on the magnitude and location of strong earthquakes anywhere in Canada after its staff review the seismic data. The review process can often take an hour or so to carry out, longer if it occurs outside normal office hours. If a significant change in the location or magnitude of the earthquake is found in the review process (a change that might alter a client response to the earthquake) ANHAS will issue a second notification message to the client with revised response actions.

5. STRENGTH OF SHAKING DETERMINED FROM EARTHQUAKE SIZE AND LOCATION

The chief output from AUTOLOC (earthquake location and magnitude) provides considerable information to a client's officers who are responding to an earthquake emergency from a control room. For example it may confirm that the magnitude was below the threshold considered (even if the strength of shaking was frightening in the control room) or that the earthquake mildly felt in the control room was in fact a strong one close to one of their remote facilities that has just gone "off the air". But our experience has been that few emergency officers are comfortable making response decisions based on such information. Simple response rules have therefore been devised based on earthquake magnitude and distance (see Section 6). Section 6 also shows why these rules are rather crude, and Section 7 indicates a better method.

The way in which strong shaking dies away with distance from the earthquake epicentre is generally understood, though the details are imprecise and involve extrapolation because we have few measurements close to strong earthquakes (especially in eastern Canada). A common measure of shaking is Peak horizontal

Ground Acceleration (PGA), expressed in terms of g or %g (where 1 g = 9.8 m/s^2). While the use of PGA for building structural design was superseded by "spectral acceleration" in the 2005 edition of the National Building Code of Canada (NBCC), PGA is still widely used as an estimator for damage and for geotechnical design. This is because force and acceleration are linearly related, and it is relatively straightforward to envision what effects might occur in a given structure shaken by a particular earthquake by considering the peak ground acceleration involved as a static push. ANHAS has continued to use the PGA relations from the 1985-1995 NBCC.

The 1995 NBCC (1995) used two regional attenuation relationships for PGA generated by earthquakes in Canada. Equations 5.1 and 5.2 are the Hasegawa et al. (1981) relations modified to base-10 logarithm.

$$\text{Eastern Canada:} \quad \log_{10}(PGA) = 0.53 + 0.56*MAG - 1.1*\log_{10}(KM + 20) \tag{5.1}$$

$$\text{Western Canada:} \quad \log_{10}(PGA) = 1.00 + 0.56*MAG - 1.5*\log_{10}(KM + 20) \tag{5.2}$$

where PGA is in units of cm/s^2, MAG is earthquake magnitude on the Richter Scale, and KM is epicentral distance in kilometres. The western equation is intended for use strictly within the Cordillera, basically British Columbia, Yukon, and western parts of Alberta and the Northwest Territories, while the eastern equation is intended for any part of Canada east of the Cordillera. Equation 5.1 is also appropriate for the northeastern U.S. These relationships are based on observations of the ground motion from some of the stronger earthquakes that have occurred in or near Canada, in some cases from direct recordings on seismological instruments or from felt and/or damage reports compiled after the earthquake. Two relationships are required because the attenuation of earthquake ground motion with distance is significantly less in eastern Canada than it is in the Cordillera. For a given magnitude, an earthquake can be felt to almost twice the distance in the eastern part of Canada than in the western (Figures 4 A and B). For earthquakes that occur near the boundary of east and west an appropriate combination of the two relations is used by ANHAS (Figure 4C).

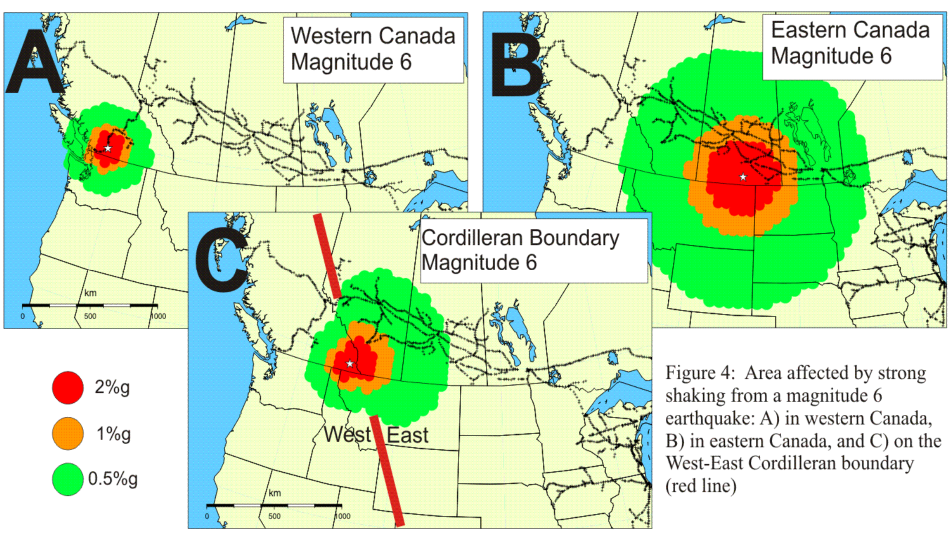

Figure 4: Area affected by strong shaking from a magnitude 6 earthquake: A) in western Canada, B) in eastern Canada, and C) on the West-East Cordilleran boundary (red line)

Other formulae may be considered as the basis for the ground motion relationships in ANHAS. In fact, the GSC has, in one case, used the accumulated earthquake recordings in a particular region to define a custom attenuation curve for a client operating in that region. However, many years of experience and development of more recent relationships indicate that the Equations 5.1 and 5.2 are conservative in nature and provide a reasonable level of confidence in the prediction of ground shaking from earthquakes. Other curves may be more efficient in the sense that they reduce the number of facilities that may be assigned to certain shaking categories (and would also reduce the number of false alarms), but as it is less certain that they will identify *all* the appropriate dams they would not increase the overall protection provided by the ANHAS system.

6. CURRENT DAM NOTIFICATION CRITERIA USED IN CANADA

A number of hydroelectric generators currently receive ANHAS earthquake notifications but each company relies on its own individual criteria to define the response required after an earthquake. These criteria are based on sets of magnitude-distance pairs, such as the ICOLD (1988) method. In one scheme "Magnitudes 4.0 to 4.9 at distances less than 80 km" is classified as *Minimal Shaking*. The weakness of the magnitude-distance type criteria is that similar operator responses are prescribed for a wide range of ground motion values. The *Minimal Shaking* criterion defined above corresponds to a wide range of ground shaking, from 0.5%g to 7%g (the latter corresponding to a magnitude 4.9 earthquake right underfoot) and with a wide range of outcomes (basically from "not felt" to possible moderate damage). A relatively short cutoff distance (180 km) is also used in some schemes, which effectively ignores the strong ground shaking that earthquakes of magnitude 6.0 or greater can cause at larger distances. A magnitude 6.5 earthquake in eastern Canada can generate peak shaking of 3%g or more to beyond 200 km. In addition, in some regions different magnitude-distance pairs are used by different operators, and this may lead to inconsistent response near provincial borders or between adjacent provincial and private dams.

6.1 Adjustments of Magnitude-distance Criteria for Eastern Canada

The same magnitude-distance pairings are not applicable in all parts of Canada, as is immediately apparent from Figure 3. Thus if some international standard such as ICOLD 1988 is applied indiscriminately it has the potential to lead to different and inconsistent responses to earthquakes in eastern and western regions. In addition, as many standards were developed from active earthquake regions, they underestimate the distance extent of strong, potentially-damaging shaking in eastern Canada. Lamontagne and Dascal (2006) suggested that the distance-underestimate might be a factor of two to six, and proposed revised magnitude-distance criteria for post-earthquake inspection of dams in Quebec based on eastern Canadian earthquake experience.

6.2 Experience with Magnitude-distance Criteria After the Nisqually Earthquake

In February 2001 the magnitude 6.8 Nisqually earthquake occurred in northwestern Washington State and strongly shook parts of southwestern British Columbia including Vancouver. At the time, ANHAS notifications to the railways were based on magnitude-distance criteria, which specified that a notification should be issued if there was a magnitude 6.0+ event within about 160 km (100 miles) of any track in western Canada. The event was located 175 km from the closest rail track in Canada, so no ANHAS notification was issued to the rail company. In fact the company was overwhelmed by reports of the earthquake from its own personnel and in the media and was chagrined not to have received an earthquake notification even though inspections subsequently showed that there was no damage done to the rail tracks by the shaking. Partly because of this experience, the criteria used by the rail companies has been changed from magnitude-distance to ground shaking (0.6%g, 1.25%g, 2.0%g) to do a better job of identifying the facilities which have experienced similar shaking. Furthermore, the extent of the notification area has been increased to 800 km to better include the effects of distant large earthquakes like Nisqually. These two features should be considered in any notification schema..

7. COORDINATED ANHAS CRITERIA FOR CANADIAN RAILWAYS

Railways comprise an extensive network of facilities, the failure of any segment of which has safety implications. For example, eastern Canadian earthquakes in 1935 and 1988 caused embankment failures (Figure 5) that broke track and so had the potential to cause derailments.

Originally, the railways also used sets of magnitude-distance pairs to define the different responses required after an earthquake. Each company had their own sets of magnitude-distance criteria that categorized the emergency response required in terms of four levels of action: 1) stop the trains, 2) slow the trains, 3) resume normal speed and 4) take no action. There had to be one set for the east and one set for the west. Different companies had different sets of rules and often reacted to the same earthquake in the same region differently.

Since ANHAS began earthquake notifications to the rail companies in 1998, the response criteria have been standardized on a scheme that uses estimated PGA from the earthquake, based on its estimated magnitude and location, at all rail lines within 500 miles of the event (Table 1). To do this ANHAS maintains a complete description of the layout of the client's rail networks, currently more than 55 000 km of track.

Figure 5: Some 300 km away from the epicentre, near Parent, Québec, earthquake vibrations triggered a 30-metre railway embankment failure, 300 km from the epicentre of the 1935 magnitude 6.2 Timiskaming Earthquake.

Table 1: Response criteria used by Canadian railways to earthquake shaking

PGA (%g)	Response
≥ 2.0	**STOP ALL TRAINS**... until inspections have been completed and appropriate speeds established by proper authority
1.25 to 2.0	**PROCEED AT RESTRICTED SPEED**... until inspections have been completed and appropriate speeds established by proper authority
0.6 to 1.25	**RESUME NORMAL TRACK SPEED**... magnitude/distance does not meet alarm criteria
< 0.6	**NO ACTION**

In the first two stages ANHAS includes within its message the specific track segments where the condition applies. The RESUME SPEED case is termed the 'near miss' condition and is intended to reduce confusion where a tremor has been felt but the shaking really was not strong enough to cause any problems to the rail lines. These cases are often exacerbated by local media reports which tend to focus on the sensational aspects of an earthquake without being clear on the limited distribution of those effects. Thus, for a strong earthquake, STOP orders may be issued for rail track close to the epicentre, RESTRICTED SPEED (i.e. slow) orders may be issued for track farther away, while, on the periphery of the shaking, RESUME SPEED orders could be issued. In the NO ACTION case, no message is sent.

Messages are transmitted via secure internet communication protocols to various centers controlling rail traffic in different regions of North America, where company personnel take appropriate action. The rail industry is highly integrated and different companies often use or connect to competitors' track, so it is important that all operators in the same region be following the same procedures.

8. POSSIBLE UNIFIED SCHEME FOR CANADIAN DAMS

In order to provide a more consistent response to earthquakes, the GSC has proposed a classification scheme based on the PGA relationships of the NBCC (Wetmiller et al., 2007). In Table 2 the strength of ground shaking, PGA, varies by a factor of 2 within each range. This is much more tightly defined than any of the current magnitude-distance ranges in use, and also avoids any overlap of ground shaking between current adjacent ranges. This example uses an optional 400-km limit for the most distant earthquakes considered and a lower magnitude limit of 4.0.

Table 2: Speculative ANHAS Inspection Schedules for Hydroelectric Facilities					
PGA classification		Suggested Inspection Deadline for Dams			
PGA (units =%g)	For M ≥ 4.0 and Distance ≤400 km	Very High CDA dams	High CDA dams	Low CDA dams	Very Low CDA dams
>10.0	Strong shaking	12 hours	24 hours	3 days	14 days
5.0 to 10.0	Moderate shaking	12 hours	24 hours	3 days	Note A
2.5 to 5.0	Weak shaking	24 hours	24 hours	14 days	Note A
1.25 to 2.5	Minimal shaking	5 days	5 days	Note A	Note A
< 1.25	No Action	N/A	N/A	N/A	N/A

Note A: the need depends on location of earthquake epicentre and the condition of dam; N/A is Not Applicable

The Canadian Dam Association (2007) Dam Safety Guidelines provide one method to classify dams by their consequence of failure. Table 2 also suggests a scheme to prioritize the post-earthquake inspection of hydroelectric dam structures according to the strength of shaking and their CDA category. While the inspection periods in the table are speculative, and not intended to be implemented without extensive discussion and refinement, they are broadly based on the inspection requirements currently used with the magnitude-distance criteria.

9. CONCLUSIONS

- The GSC has nearly 10 years experience operating a national earthquake alert system serving the transportation and energy infrastructure, and has benefited from collaboration from its clients.
- It has become apparent that existing response schema are *ad hoc* and may used out of context, meaning that the quality of response may be compromised. Improved schema should be based on the predicted seismic ground motions (not just magnitude and distance) that have been estimated using appropriate regional attenuation studies.
- Improved schema will ensure that facilities which experience similar levels of ground shaking will be attended to in a consistent and timely fashion, and will also help avoid over-reaction and unnecessary downtime for weak earthquakes.
- A facilities-based damage classification, pre-decided with the client and based on vulnerability, should be used (for example, railway embankments are more vulnerable than dams).
- These lessons have general application to the safe operation of large-scale engineering facilities such as hydropower systems, railways, pipelines and mines.

Acknowledgements
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