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RESERVOIR-TRIGGERED SEISMICITY IN THE CANADIAN SHIELD

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ABSTRACT

The International Commission on Large Dams (ICOLD) has recently published a Bulletin on Reservoir-Triggered Seismicity (RTS). The Bulletin, in its rough draft stage, reviews the state of knowledge on this phenomenon, and suggests a methodology to assess its likelihood in various tectonic contexts. In light of future development of hydro-electric reservoirs, we examine how this Bulletin applies to the Canadian Shield environment, i.e. a mostly seismically quiescent region that contains some active areas and five documented cases of RTS. We find that some generalizations contained in the Bulletin should be refined in light of the known RTS history in the Canadian Shield. According to the Bulletin, for example, the thrust faulting environment and the quasi absence of background seismicity make RTS unlikely in the Canadian Shield, in contradiction to the known RTS history. Another example is that the Bulletin describes reservoir-triggered earthquakes as tectonic events that occur prematurely because of the increase in pore-fluid pressure. Based on this, one could consider the regional earthquake activity representative of the potential for RTS, even though tectonic earthquakes in the Canadian Shield generally occur much deeper (5-30 km depth) than RTS (upper 1-2 km depth). We present some preliminary ideas on the assessment of RTS potential in the Canadian Shield, keeping in mind the difficulty in forecasting the impact of increased pore fluid pressures on faults that are generally unmapped, have an unknown neotectonic history and lack sufficient knowledge of their permeability. The problem of defining a representative RTS event (location, magnitude, depth) for the design of dams and appurtenant structures is also examined.

Introduction

Reservoir-Triggered Seismicity (RTS) occurs when pre-existing faults are brought to rupture by an increase in pore-fluid pressure and possibly, by the added weight of reservoirs. The possibility of RTS should not be neglected by dam designers: there are a few worldwide examples of RTS main shock exceeding magnitude 6 on the Richter scale. In addition, the main shock of an RTS sequence represents a higher hazard than a tectonic earthquake of similar size: its focus is much shallower (generally a few kilometers below surface) and potentially closer to a dam and its appurtenant structures.

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Up to 2008, very few documents provided information on how dam designers should take into account the potential RTS hazard. The document ICOLD (2008), still in rough draft stage as of October 2009, describes factors that favour the occurrence of RTS and suggests ways to consider this hazard in the design of dams and appurtenant structures. It suggests studies to evaluate the possibility of RTS in various seismotectonic environments. Currently, it can be considered the most complete description of RTS for the designers of dams, much better, in our opinion, than the general descriptions found in USCOLD (1997) which did not provide much guidance on how to approach this hazard. The review remains general in nature and, for this reason, does not covers the characteristics of intraplate environments such as the Canadian Shield.

In light of the ongoing development of large hydroelectric reservoirs in eastern Canada, we have examined the applicability of some inferences of ICOLD (2008) to the context of the Canadian Shield. We suggest ways to make them more adapted to this geological environment. It is hoped that this report will help clarify the RTS potential in the Canadian Shield for design purposes and environmental assessments of hydroelectric projects. The current report does not review the extensive documentation on RTS synthesized in ICOLD (2008) and USCOLD (1997), but adds some information on RTS in the Canadian Shield not contained in these two documents.

RTS history in the Canadian Shield

The Canadian Shield is the core of the North American continent and is made up of Precambrian rocks of various lithologies. The Shield is intensely faulted and fractured at the regional scale as well as the very local level. The Canadian Shield is currently an intraplate environment where most tectonic earthquakes concentrate in certain areas where most historical earthquakes (some as large as magnitude 6 to 7) also occurred. Except for these active zones, most areas of the Canadian Shield have very little earthquake activity on any given year. For this reason, most of the Canadian Shield can be referred to as a stable craton due to its absence of current tectonic activity and very low level of earthquake activity. It is an intraplate region and as such, no tectonic activity (localized deformation or seismicity) is taking place in most of it. Estimates of the strain rate in most of the Shield (10^{-13}–10^{-10} $yr^{-}1$; Mazzotti and Adams, 2005), is much smaller than those measured near plate boundaries (interplate environments). Ridge push and post-glacial rebound are probably the main contributors to tectonic stresses. The last tectonic events that affected the eastern edge of the Canadian Shield were probably related to the opening of the Central Atlantic in the Jurassic, and/or to extension and seafloor spreading of the North Atlantic during the Cretaceous (≈ 65 Ma; Tremblay et al., 2003). The only known neotectonic activity of the Canadian Shield is the surface rupture associated with the 1989 M 6.1 Ungava earthquake of Northern Quebec.

As far as the RTS is concerned, the Canadian Shield has had five documented cases (all in Quebec), the largest main shock being the 1975 magnitude $m_b(L_g)$ 4.1 near Manic 3 (Table 1). All five cases occurred outside zones of enhanced earthquake "tectonic" activity, but three (Manic-3, SM-3, Toulnustouc) were within 100 km of the Lower St. Lawrence Seismic Zone whereas the remaining two (LG-2 and LG-3) were remote from significant tectonic earthquake activity. Most RTS events occurred within a few years of the reservoir impoundment. The RTS history near Manic-3 and Toulnustouc, for example, reveals hundreds of earthquakes in the few months following the October 1975 main shock, followed by years with almost no activity.

We must note that RTS detection depends largely on the capacity of the seismograph network. For this reason, we cannot discard the possibility that some RTS (albeit of small magnitude) was not detected when large reservoirs were created. This is especially true before the 1960s when the detection level of the seismograph network was not as good. Currently, any event above magnitude 3.0 would be detected, with many areas of the Shield where it could be much lower.

The few focal mechanisms of RTS events that exist suggest that reverse faulting on pre-existing zones of weakness (most probably ancient faults) is the principal mode of fault reactivation. These events most probably represent relaxation of near-surface stresses and their relationship with deeper deformation is uncertain.

A plot of reservoirs depth versus capacity with RTS cases (a "scatter graph") is much used to show that most occur if reservoirs exceed 100 m depth and/or 10^9 m^3 capacity (USCOLD, 1997; ICOLD, 2008). We have drafted the same type of graph for Canadian reservoirs (Fig. 1). The graph clearly shows that very few reservoirs triggered seismicity in Canada and the few with RTS were among the largest. However, many large and deep reservoirs in the Canadian Shield had RTS. Four out of the five RTS cases occurred outside the much discussed threshold of 100 m reservoir depth and 10^9 m^3 reservoir capacity. An aspect that should be kept in mind, however, is that some of the largest and deepest reservoirs did not have local seismograph networks at the time of impoundment. The detection level was such that it is possible that microseismic events occurred but remained undetected. An exception is the Mica dam that was closely monitored at time of impoundment in 1973 but did not trigger undisputable RTS (Ellis and Chandra, 1981).

The potential for RTS in the Canadian Shield

We comment on ideas on RTS potential in the Canadian Shield using the ICOLD (2008) as a basis for discussion.

1. RTS versus tectonic earthquakes

ICOLD (2008) suggests that RTS is similar to tectonic earthquakes as both types of seismicity have similar focal mechanisms and respond to similar rock mechanics principles. In essence, a reservoir-triggered event is a tectonic earthquake that had its time of occurrence advanced by the increase in pore-fluid pressure. We note however that most tectonic earthquakes occur at larger depth (5-30 km) than RTS earthquakes which are relatively superficial events (most at 2 km depth or less). One must also note that superficial tectonic events in the Canadian Shield are rare but can be significant: in 1989, a M 6.1 earthquake occurred in the Ungava peninsula of Northern Quebec and caused the first documented surface rupture in eastern North America (Adams et al., 1991). Most Miramichi, New Brunswick, earthquakes were also shallower than 5 km (Wetmiller et al., 1984). It is unclear at this time if reservoir impoundment could increase the pore fluid pressure at seismogenic depth where most events of the Canadian Shield occur (5-

25 km depth in the seismic zones of Charlevoix, Lower St. Lawrence and Western Quebec).

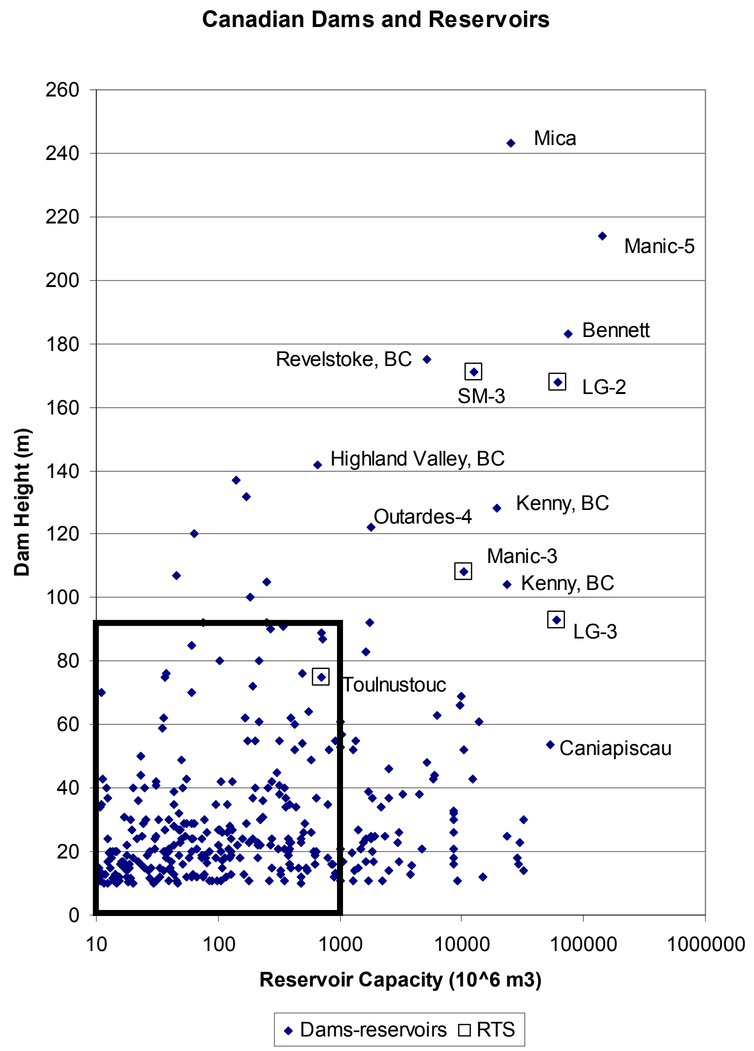

Fig. 1 Plot of the dam height versus the capacity of reservoirs in Canada. The dam height is taken as a good representation of reservoir depth. Reservoirs with RTS (see Table 1 for a list) are shown as squares (Source of base information: the CDA, 2003).

In our opinion, ground motions of a generic RTS event could be defined as it is done for a tectonic event in the near-field. In the Canadian Shield environment, since the 1975 Manic 3 earthquake was not recorded by accelerographs, the impact of a similar event of this magnitude in the near field can be assessed using accelerograms and spectral signature recorded from shallow focus aftershocks of the 1982 Miramichi earthquake, New Brunswick, Canada (m_N 4.8 and m_N 4.0; Earthquake Canada web site). More theoretical approaches could also be used.

Table 1. Documented cases of RTS in Canada (all in the Canadian Shield of Quebec).

Name of dam	Reservoir capacity ($X10^9$ m^3)	Max. depth	Water depth at time of main shock	Main Shock	Focal depth of RTS	Date of largest RTS event	Level of RTS	Zone	Reference
Manicouagan-3 (Manic-3)	10.1	102 m	76 m	4.1 $m_b(L_g)$	0 - 2 km	1975-10-23	Moderate	2-3	Leblanc and Anglin (1978)
La Grande-2 (LG-2)	61.7	145 m	90 m	0.9 M_L	< 5 km	1979-02-05	Micro-earthquake level	1	Buchbinder et al. (1981)
La Grande-3 (LG-3)	25.2	88 m	78 m	3.7 M_L	< 5 km	1984-04-24	Moderate	1	Anglin and Buchbinder (1985)
Sainte-Marguerite 3 (SM-3)	12.6	142 m	90 m	2.2 m_N	1-2 km	2000-05-31	Micro-earthquake level	2	Lamontagne et al. (2006)
Toulnustouc project	0.7 added in 2005 (total: 2.8)	72 m	72 m	1.6 m_N	1 km	2007-02-09	Micro-earthquake level	2	Lamontagne et al., (2008)

Legend:

Max. depth: Maximum depth of the reservoir
Main shock: Magnitude of the Main Shock and Magnitude Type
Zone: Seismic Zone used by Hydro-Québec (0: low; 5: high)

2. Tectonic environment

ICOLD (2008) states that RTS is less likely in thrust (reverse) faulting than in normal or strike-slip faulting environments. The Canadian Shield is a reverse faulting environment but has had a few cases of RTS (Table 1). The Canadian Shield is an area with the maximum compressive stress is sub-horizontal causing fault reactivation mainly as reverse-faulting. Although no single-event mechanism exist for RTS events, this is known from focal mechanisms of tectonic earthquakes and from two composite mechanisms of Manic-3 events (Leblanc and Anglin, 1978). Additional information such as well breakouts also suggests a NE-SW general direction for the maximum compressive stress (Adams et al., 1991).

3. Depth of reservoir

It is generally suggested that the likelihood of RTS is greater if the depth of the reservoir exceeds 100 m. The water height is directly related to the increase in hydrostatic pore fluid pressure. There is no reason to believe that lower water pressure cannot be sufficient to trigger RTS, a fact recognized by ICOLD (2008). According to rock mechanics principles, slip occurrence depends on how close to rupturing the fault is prior to filling of the reservoir. Three out of the five eastern Canadian RTS cases of Table 1 have water height less than 100 m. For the RTS at Manic-3 for example, the water height was only at 50 m when RTS started and had reached 76 m when the main shock occurred (Leblanc and Anglin, 1978). At LG-3, RTS occurred when the water depth was only 64 m. If a headrace tunnel in bedrock exists, as in Sainte-Marguerite-3 and Toulnustouc, Quebec, one has to consider the total water head not only the reservoir depth. Likewise, a reservoir depth in excess of 100 m does not necessarily imply RTS. The best example is the Manic-5 dam that has a height of 214 m but had no RTS detected (Leblanc and Anglin, 1978; see also Fig. 1). In conclusion, the 100 m threshold does not define the RTS potential in the Canadian Shield.

4. Weight of water

The water weight increases the vertical stress directly on the rocks beneath the reservoir. In a reverse faulting environment such as eastern Canada, this increase in vertical stress increases the least compressive stress (F'_3) directly under the reservoir. Unlike the diffusion of pore-fluid pressure through fracture media, the stress transfer is immediate and RTS should appear immediately.

RTS experience in the Canadian Shield suggests that the impact of reservoir weight is secondary. At Toulnustouc, the second largest reservoir-triggered earthquake (m_N 1.4) occurred 16 days after the flooding of the new portion of the reservoir which took place over a period of four days (Lamontagne et al., 2008). The Toulnustouc project involved the flooding of an additional portion (0.7 X 10^9 m^3) of an already existing reservoir (pre-existing volume of 2.1X 10^9 m^3). The delay between the added weight (instantaneous) and the triggering (delayed) of the earthquake suggests that it is really the diffusion of the water pressure that triggered the event. The largest earthquake occurred almost two years after flooding. Similarly at SM-3, low magnitude RTS occurred near the intake tunnel as soon as it was flooded, a clear indication that the pressure diffusion is more important than the added weight (Lamontagne et al., 2006). The added weight may have some impact however. If a fault extends beyond the shoreline of a reservoir, it is possible that the added weight increases the likelihood of RTS. This may have been the case in SM-3 and Toulnustouc, where most RTS was outside the outlines of the reservoirs, not directly beneath. This is probably true for most other RTS cases of Table 1.

5. Water level variation

ICOLD (2008) mentions that water level variations appear to be related to RTS in some reservoirs worldwide. This aspect may be important where there are important seasonal water level changes that send pore-fluid pressure pulses at depth. Studies of this possible correlation in Canadian Shield reservoirs such as Manic-3, LG-2, and LG-3 have not been very conclusive (Leblanc and Anglin, 1978; Buchbinder et al., 1981; Anglin and Buchbinder, 1985). At Manic-3, where annual water level variations are smaller than 1 m, there were a few micro-earthquake triggered events.

6. Presence of geological faults

ICOLD (2008) suggests the careful examination of faults in the surroundings of a reservoir. In this respect, guidelines on neotectonics and dams can be found in ICOLD (1998). In the Canadian Shield context, faults are often difficult to observe directly except where the overburden is removed or where the fault crosses a river bed or a valley with exposed cliffs. This is often the case in the immediate construction site, but rarely done over the whole length of the reservoir. Very often, large reservoir can be tens of kilometres long, which, in the Canadian Shield context, implies that they probably intersect faults left by geological events that occurred millions or even billions of years ago. In almost all areas of the Canadian Shield, remote sensing imagery, such as satellite images and air photographs, reveal numerous lineaments that can be structural or lithological in nature. Existing geological maps are not necessarily helpful in the Canadian Shield: they often represent lithological information at regional scale with little or no information on geological structures such as faults, joints or lineaments. In general, even if a lineament can be recognized as a fault, it is not certain that the fault can be seen at the surface due to the surficial cover (very often glacial deposits).

ICOLD (2008) suggests that faults with dimensions corresponding to the maximum magnitude for an RTS event (M 6.0 to 6.3) be examined. The scaling law for a moment magnitude (M_w) 6.0 intraplate earthquake suggests a fault dimension of 8 km by 4 km with a slip of 0.91 m (Johnston, 1993; Table 2). Faults with such dimensions can be found almost anywhere in the Canadian Shield. For the Ungava earthquake and for all RTS cases of Table 1, there was no clear link with a known and recognizable fault.

7. Neotectonic activity/ Recent movement on a fault

A fault can sometimes be recognized as active if studied with neotectonic analyses. Guidelines on this type of analysis can be found in ICOLD (1998). In general, any fault activity during the Holocene (last 10,000 years) indicates that the fault should be considered active. In southeastern Canada, the Holocene corresponds to the retreat of the continental glaciers. In the Canadian Shield, only one surface rupture has been documented: the fault rupture due to the 1989 Ungava earthquake. It was also shown that the surface rupture occurred on a fault that is not distinct from thousands of others in the Canadian Shield.

Concerning the risk of having a surface rupture going through the dam, one can assume that the removal of surficial material and cleaning of the rock surface that occurs prior to the construction would reveal the presence of a fault, and possibly evaluate if neotectonic reactivation has taken place. One must note, however, that most indented river valleys of the Canadian Shield follow lineaments, very often correlated with geologically-old faults. One could assume that if the surface of the fault has been polished by the glacier flow, this could indicate that the fault has not been active since deglaciation (which corresponds to the Holocene, i.e. ≤ 10,000 yrs in southeastern Canada).

2.1. Defining the characteristics of the design reservoir-triggered earthquake

Without going in the details of how the design earthquake should be defined, one could suggest the following. The Maximum Credible Earthquake, through its indirect relationship with the fault length, does not appear to be a workable approach in the Canadian Shield for reasons explained above (see section on faults). Earthquakes in the Canadian Shield can reach or exceed M 6.0. Earthquakes of this size are known in many seismically active areas. According to the current understanding of earthquake hazards, these earthquake occurrences are closely related to the reactivation of Iapetan rift faults that break the integrity of the Craton. For areas where these faults are not present, earthquakes in the magnitude 5 to 6 range are infrequent but possible. It seems to us that a maximum magnitude of 6.0 to 6.3 for RTS is too high for the Canadian Shield context. We would support this by the focal depth of most Canadian Shield earthquakes and the relationship between most M 6+ earthquakes and Iapetan Rifted Margin (Mazzotti and Adams, 2005). Proximity to these faults, however, should be examined as possible source of RTS.

In the case of Manic 3, the magnitude of the largest reservoir-triggered earthquake reached $m_b(L_g)$ 4.2 (corresponding approximately to M_w 3.7). Consequently, in absence of any other approach to estimate the potential reservoir-triggered earthquake, this magnitude should be considered a good example to be used in modelling an RTS main shock in the Canadian Shield. For modelling purposes, the earthquake epicentre should be located beneath or near the reservoir in a standard manner for deterministic calculations.

So in our opinion it appears adequate to consider RTS history in geologically similar areas and assume a similar magnitude for a RTS main shock located in the surroundings of a reservoir in the Canadian Shield at the time of its impoundment and for a few years period after.

Discussion and Conclusions on RTS in the Canadian Shield

With the current state of knowledge, RTS appears possible anywhere in the Canadian Shield even in areas assumed to be tectonically stable from tectonic deformation or seismic activity. Although conditions leading to reactivation of faults are sufficiently relatively well known from theoretical approaches, they are never known in sufficient detail to exclude this possibility in the Canadian Shield. This assumption is valid irrespective of the distance to a recognized seismic zone or the background seismicity at the site. The magnitude of the main shock of the RTS can be estimated by a seismic hazard analysis that would consider the history of RTS in the Canadian Shield, and not in the whole world.

RTS history can be used as analogues to geologically similar areas. For the Canadian Shield, the maximum magnitude for an RTS main shock was $m_b(L_g)$ 4.2 (corresponding approximately to M_w 3.7) in the Manic 3 reservoir in 1975. By lack of other sources of knowledge on fault properties, it appears adequate to assume a similar magnitude for a RTS main shock located in the surroundings of a reservoir in the Canadian Shield at the time of its impoundment and for a few years period after. The probability of such an event should be discussed when a project is examined.

A generic RTS event should be defined with ground motion characteristics similar to a tectonic event in the near-field. In the Canadian Shield environment, since the 1975 Manic 3 earthquake was not recorded by accelerographs, the impact of a similar event of this magnitude in the near field can be assessed using accelerograms and spectral signature recorded from shallow focus aftershocks of the 1982 Miramichi earthquake, New Brunswick, Canada (m_N 4.8 and m_N 4.0; Earthquake Canada web site).

In certain areas with low seismicity, such as parts of the Canadian Shield, the main shock from an RTS may eventually represent the design earthquake. This is especially true in areas remote from recognized seismic zones of the Canadian Shield, where the main shock of an RTS may exceed the seismic provisions calculated from probabilistic approaches and used for the design of dams.

At present, the "rule of thumb" of 100m reservoir depth for potential RTS is a crude approximation representing the passage to a more important dam category. Consequently, 100 m water depth does not appear to be the major controlling factor in the Canadian Shield. It is logical to think that RTS is more probable, although far from certain, when water depth is greater than 100 m

Determining maximum earthquake magnitude from fault length is not applicable to an intraplate area such as the Canadian Shield. Faults (lineaments) are found on all scaleS and are due to past geological events. Documenting Quaternary neotectonic activity of these lineaments is close to impossible in the Canadian Shield because of the history of glacial episodes in the last million years. Except where bedrock is exposed, Holocene neotectonic activity (< 10,000 years) is also difficult to document near large reservoirs that are very often crossed by a large numbers of lineaments with few markers for neotectonic ruptures.

The duration of RTS activity in the Canadian Shield does not appear to exceed a few years after impoundment. This is important to mention to avoid monitoring for extended periods of very low level seismicity.

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