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M_{min} − IMPLICATIONS OF ITS CHOICE FOR CANADIAN SEISMIC HAZARD AND SEISMIC RISK

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ABSTRACT

Probabilistic seismic hazard analyses consider the contribution of ground motions from a range of magnitudes. The choice of maximum magnitude (M_{max}) is often the source of considerable debate. However, the choice of minimum magnitude (M_{min}) can also have a significant effect on the resulting hazard. This is especially true for peak ground acceleration (PGA) and short period hazard values in regions of low seismicity where the majority of the hazard contribution comes from small earthquakes at nearby distances. This is doubly so in eastern North America where PGA ground motions are high in amplitude, even from relatively small magnitude events. Long period hazard, and hazard for all periods calculated for low probabilities are minimally affected by the choice of $M_{min.}$ When hazard values are applied to liquefaction analysis or to the design of short-period structures, especially non-brittle ones, it appears one has to decide whether the true "scientific" hazard (contributions from all earthquakes) or an "engineering" hazard from earthquakes larger than a minimum-magnitude cutoff is appropriate.

Introduction

The choice of maximum magnitude (M_{max}) for source zones contributing to seismic hazard has traditionally drawn the attention of both seismic hazard modellers and engineers (e.g., Wheeler, 2009). The choice of minimum magnitude (M_{min}) has garnered less interest but its importance has been recognized for some time (e.g., Bender and Campbell, 1989). In Canada, we believe (but are still trying to verify) M_{min} was set at 0 for the seismic hazard maps in the 1985 and 1995 editions of the National Building Code of Canada (NBCC). Thus, the hazard maps included contributions from very small earthquakes. For the 2005 (and 2010) editions of the code, a M_{min} of 4.75 was used to estimate seismic hazard. This lower bound cutoff recognized the contemporary engineering consensus that smaller earthquakes would probably not generate ground motions that would be of importance to engineered earthquake-resistant structures (Adams and Halchuk, 2003).

It should be noted that the magnitudes used in defining the source zone relations for western and eastern Canada are different. Western sources use local magnitudes (M_L) that are

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considered numerically equivalent to moment magnitude (M_w), while eastern sources use a body wave magnitude (M_{bLg}). The current M_{min} value, M_{bLg} 4¾ is roughly the same as M_w 4¼. Allowing smaller magnitude events to make a contribution to the hazard in eastern Canada was a recognition that small magnitude events in this region generate higher peak amplitudes and over larger distances than observed in the west. In a similar manner, the United States Geological Survey currently applies its minimum magnitude of 5.0 as moment magnitude in the Western United States but as M_{bLg} in the Central and Eastern United States (Petersen et al., 2008).

M_{min} and Ground Motion Prediction Equations

In western Canada, the ground motion prediction equations (GMPE) used were Youngs et al., 1997 and Boore et al., 1993, 1994 (see Adams and Halchuk, 2003 for details of their use). For eastern Canada, Robert Youngs (pers. comm.) provided a suite of 8-parameter equations that are a better fit to the Atkinson Boore 1995 look-up table values than the quadratic equations provided in Atkinson and Boore. We used Youngs' approximation equations for earthquakes with magnitudes of 5 or greater. It should be noted that the western equations used are also limited to earthquakes in the magnitude range M_w 5-8. In this sensitivity study the GMPEs have been extrapolated downwards beyond their intended range of magnitudes and the results may less accurate for the M_{min} values below 5.0.

We note that future GMPEs need to be applicable for earthquakes with magnitudes of less than 5, if the M_{min} is to be chosen smaller than magnitude 5. Not all the current suite of Next Generation Attenuation (NGA, Abrahamson et al., 2008) ground motion equations (intended for California-type environments) are applicable to earthquakes with magnitudes of less than 5.

Effects of M_{min} on Canadian Hazard Calculations

Previous studies (Halchuk et al., 2007) found that shifting the minimum magnitude could have a significant effect on peak ground acceleration (PGA) values. Variations in PGA values of more than 50% were noted when M_{min} values were allowed to vary between 4.25 and 5.5. This effect is more significant in regions of low seismicity where the truncation has a greater influence (e.g., Figure 1). The consequences should be of particular interest to geotechnical engineers when PGA is used in liquefaction analysis. For this sensitivity study, the value of M_{min} was allowed to vary between 4.0 and 5.5, and the tests were also performed on spectral values.

The effect of M_{min} choices on the uniform hazard spectra for selected Canadian cities is shown for the NBCC annual probability of 0.000404 (2%/50 years) in Figure 2. In regions of high seismicity (Vancouver and Montreal), the effect is minimal - less than 5% across the spectrum (from 0.1 to 2.0 seconds). In lower seismicity regions (Toronto, Winnipeg), the difference in hazard is significant at short periods. The spectral acceleration at 0.1 seconds (Sa(0.1)) values drop by as much as 45%. PGA values are not included in the uniform hazard spectra plots, but are listed in Table 1. The effect of M_{min} choices on PGA values is similar to that seen on short-period hazard values.

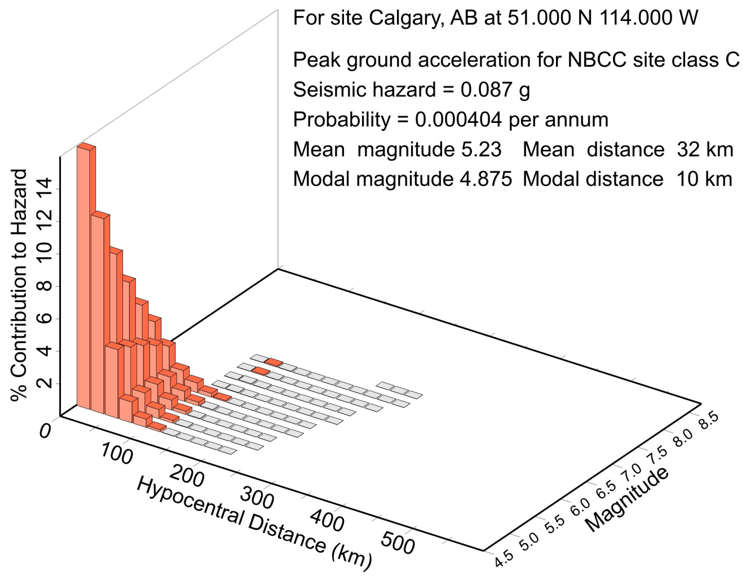

Figure 1. Deaggregation of PGA for Calgary at the NBCC probability of 0.000404 p.a. showing the truncation of hazard contributions from earthquakes less than 4.75.

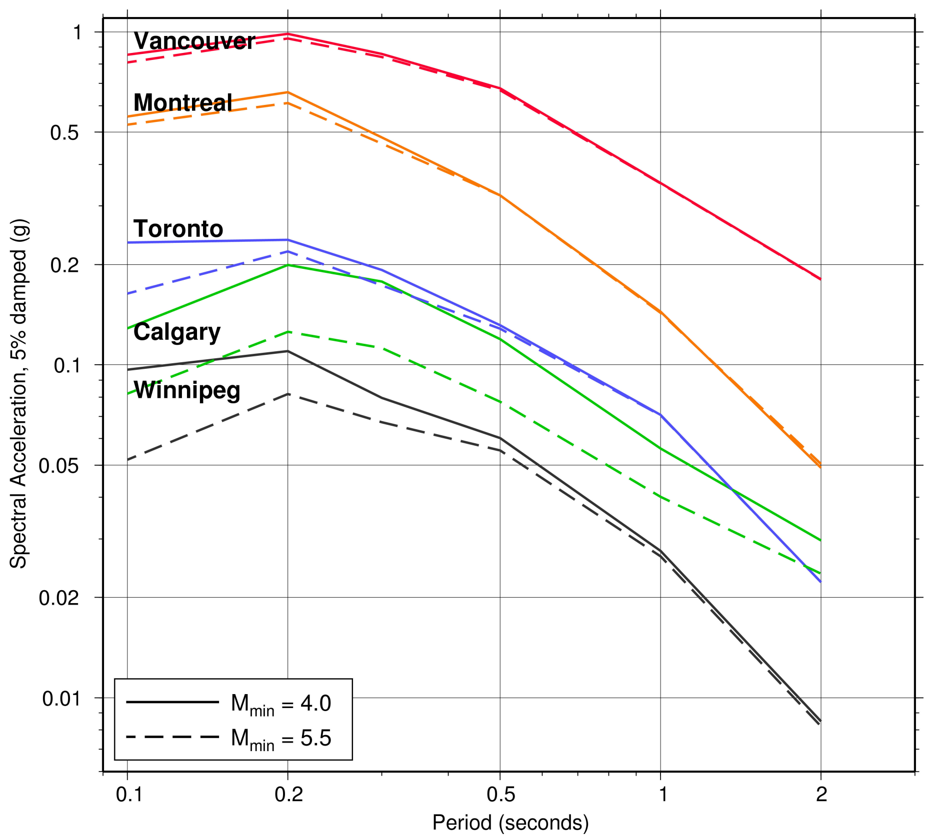

Figure 2. Uniform hazard spectra for selected Canadian cities at the NBCC 2010 probability of 0.000404 per annum. For each city, solid lines show the results from $M_{min} = 4.0$, dashed lines show the results from $M_{min} = 5.5$.

Table 1. Effects of minimum magnitude cutoff on peak ground acceleration values at 2%/50 year probability. Note these are values intended for NBCC 2010.

City	**2%/50 year peak ground acceleration (g) at different magnitude cutoff values**						
	4.0	4.25	4.5	4.75	5.0	5.25	5.5
Vancouver	0.493	0.491	0.488	0.485	0.479	0.472	0.462
Montreal	0.365	0.356	0.340	0.332	0.329	0.306	0.281
Toronto	0.131	0.128	0.123	0.123	0.114	0.102	0.088
Calgary	0.127	0.114	0.101	0.086	0.065	0.054	0.043
Winnipeg	0.057	0.052	0.042	0.036	0.031	0.027	0.025

Calgary is an anomalous location in terms of the effects. Hazard values drop significantly (25-40%) across the entire spectrum. We believe this to be a combination of at least two factors: (i) The source zone providing the bulk of the hazard to Calgary has a small M_{max} value (6.0), meaning that smaller magnitudes contribute a larger proportion of the hazard even at longer periods, and (ii) The source also has a steep magnitude recurrence slope (b = 1.08). Larger earthquakes are thus rare compared to smaller events, and the distribution results in smaller contributions from the distant larger earthquakes that contribute most of the long period hazard in zones with more typical b values. This reiterates the findings of Beauval and Scotti (2004), whose work showed that sites with steeper recurrence slopes have a higher sensitivity to the choice of a minimum magnitude.

Higher probability (or shorter return period) hazard calculations are affected to a greater extent than lower probability results (Figure 3). While the relative change in hazard values more than doubles as one increases the probability from 0.000404 p.a. to 0.01 p.a., the absolute changes are relatively small. The probability effect decreases with increasing seismicity rate. The effect of increasing the probability level can be seen in more detail on the Sa(0.2) values for Toronto (Figure 4). Increasing the M_{min} from 4.0 to 5.5 causes hazard values to drop by 10% at 0.000404 per annum. At 0.01 p.a. probability, this drop increases to 40%.

Consequences

The effects of different choices for M_{min} on hazard values has been outlined above. For deaggregation studies the key parameters are the modal and mean magnitude-and-distance (Fig. 1). At NBCC probabilities of 0.000404 p.a., the modal earthquake contributing to hazard for several localities in Canada occurs close to M_{min}, particularly for short period Sa(0.2) and PGA (Halchuk et al., 2007). Some examples are: St. John's, Halifax, Windsor, Winnipeg, Calgary (Fig. 1), Kelowna, Prince George, Prince Rupert, Inuvik - generally sites without many nearby earthquakes. Shifting the choice of the M_{min} higher or lower in these cases would have particularly large effects, not only on the hazard values but also on the contributing modal magnitude. When the mode is near the edge of a sampled distribution, shifting the edge of the distribution (in this case the lower edge) will often see a shift in the mean and mode distribution (Table 2). This shift could have consequences in liquefaction analyses, which uses PGA together with a representative magnitude (which is an alias for earthquake duration). Thus liquefaction gets a double effect – the mode changes <u>and</u> the actual value of PGA depends on M_{min}.

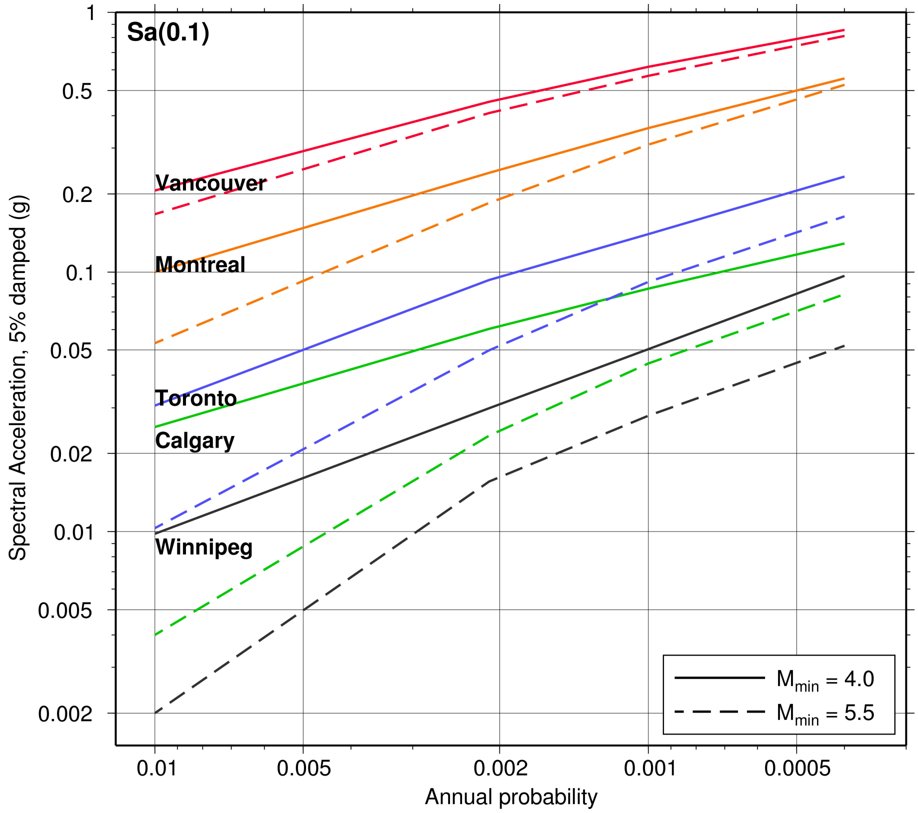

Figure 3. Short-period (Sa(0.1)) hazard curves for selected Canadian cities. For each city, solid lines show the results from M_{min} = 4.0, dashed lines the results from M_{min} = 5.5.

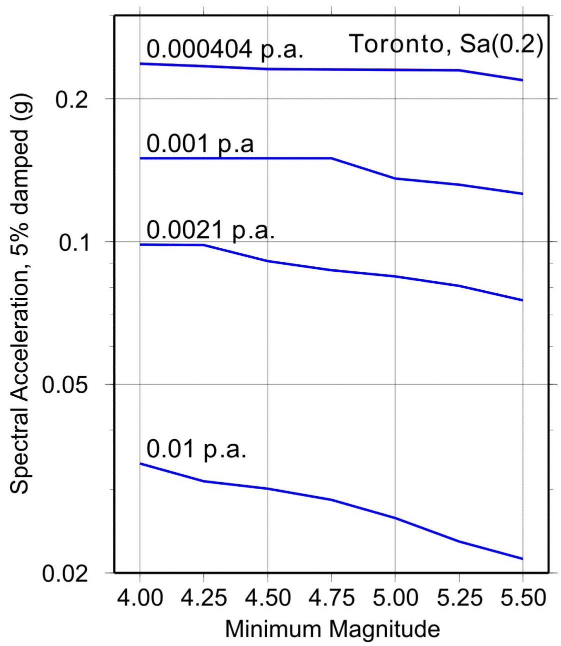

Figure 4. Variation in Sa(0.2) values with increasing minimum magnitude for Toronto at four different probabilities.

Table 2. Effects of minimum magnitude cutoff on mean and modal magnitude values at 2%/50 year probability for Calgary (note magnitude bins are ¼ units wide).

Calgary	**4.0**	**4.25**	**4.5**	**4.75**	**5.0**	**5.25**	**5.5**
Mean M	4.71	4.88	5.05	5.23	5.41	5.59	5.79
Modal M	4 $^{1}/_{8}$	4 $^{3}/_{8}$	4 $^{5}/_{8}$	4 $^{7}/_{8}$	5 $^{1}/_{8}$	5 $^{3}/_{8}$	5 $^{5}/_{8}$

Discussion

There does not appear to be global consensus on the most appropriate M_{min} value. North America employs M_{min} values of 4.75 - 5.0. Beauval and Scotti (2004) note that lower M_{min} (3.5 – 4.0) have been used in Europe. Grünthal and Wahlström (2001) suggest that large portions of the hazard could come from these smaller events. The range of M_{min} values reflects the differing philosophies for the choice of the minimum magnitude. From a purely scientific calculation, all magnitudes contribute to the hazard (in practice a minimum value of 0 would be used in the integration to obtain hazard). From an engineering perspective, these small magnitudes are often thought to have a negligible impact on the risk as they are very unlikely to produce damaging ground motions, particularly damage that causes collapse and threatens life-safety. The difficulty arises in determining the threshold for significant damage that can be addressed in building codes.

Different minimum magnitudes may be appropriate for different structures. Nuclear power plants have limited vulnerability to the short duration and high frequency of $M_w < 5$ earthquakes (Harmsen, *pers. comm.,* 2008). This is not the case for short-period buildings. The September 3, 2000 Napa, California earthquake (M_w 5.0) produced recorded PGA of 0.49g, caused significant damage, and resulted in direct losses estimated at more than $US50 million (EERI, 2000). Earthquakes of a given magnitude can produce a very wide range of shaking, with the upper-tail shaking levels an order of magnitude larger than the median (+3 sigma; Strasser et al. 2009). Directivity is one effect that can produce higher-than-average shaking levels and thus increase losses significantly, even for relatively small magnitude events. If the M_{min} is chosen too high, these upper-tail contributions from smaller earthquakes will be ignored.

Ignoring the upper-tail contributions from smaller earthquakes is probably acceptable if they make only a small contribution to the total seismic hazard; furthermore if due to directivity the upper-tail contributions are likely to have much energy at short periods together with a very short duration of shaking. Hence they should pose low damage potential for robust short-period structures that have structural redundancy and considerable reserve strength beyond the elastic limit ("ductile and robust" buildings with graceful failure modes). By contrast, brittle structures (that might suffer complete failure just beyond their elastic limit) such as older brick homes may not exhibit graceful failure, and so need to be designed for the higher levels of seismic hazard coming from a lower M_{min}. Note that although the necessary M_{min} is probably a function of building type, it is likely impracticable to use different M_{min} for different structural types, and so a likely outcome is a compromise in which a single M_{min} is used for national seismic hazard maps but the loading part of the code (R factors) requires resistance to larger loads for brittle structures to increase their performance against collapse.

Past choices of M_{min} for national building codes were influenced by the history of damage to short, brittle structures such as unreinforced brick houses. Although the damage to these may be severe and costly (e.g., in the case of Newcastle, Australia (Dhu and Jones, 2002)), national building codes in fact do little to reduce the economic loss that a design-level earthquake may cause to these types of structures. Therefore it is possible that a higher M_{min}, together with changes in the engineering approach, might be a more rational choice if implemented in a broader (economic, social) environment that recognizes earthquake mitigation can be achieved by methods other than building codes.

Conclusions

The choice of minimum magnitude (M_{min}) can have a significant effect on the computed seismic hazard, especially true for PGA and short period hazard in regions of low seismicity where the majority of the hazard contribution comes from small earthquakes at nearby distances. Long period hazard, and hazard for all periods calculated for low probabilities are minimally affected by the choice of $M_{min.}$ When hazard values are applied to liquefaction analysis or to the design of short-period structures, especially non-brittle ones, it appears one has to decide whether the true “scientific” hazard (contributions from all earthquakes) or an “engineering” hazard from earthquakes larger than a minimum-magnitude cutoff is appropriate.

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