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# AN OVERVIEW OF DEVELOPMENTS IN SEISMIC HAZARD ANALYSIS

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## SUMMARY

Developments in seismic hazard analysis over the last few decades are overviewed, and a perspective is presented on current issues and new developments. Over the last 30 years, methods and data have been refined, but our overall understanding of seismic hazards in most regions, as applied to typical building codes, has not changed very much. Our seismic hazard zoning maps are a relatively simple and transparent consequence of the patterns of historical seismicity. Over time, we have refined our understanding of where and why earthquakes occur, and improved our characterization of the resulting ground motions and their probabilities. We have begun to understand the important role of uncertainty in seismic hazard analysis. However, there are still significant shortcomings in our treatment of uncertainty. The same lack of knowledge that causes our uncertainty of the hazard also prevents us from accurately quantifying that uncertainty. At present, new ground-motion data, available in near-real time, are allowing better insight into earthquake ground motion generation and propagation, and are laying the groundwork for real-time seismic hazard information systems that will be developed in the future.

## HISTORICAL OVERVIEW OF HAZARD ANALYSIS

Seismic hazard analysis has been an element of good engineering design practice in modern countries for many decades; it is an integral component of building codes and standards for design of critical structures such as dams, offshore structures and nuclear power plants. This overview begins with a historical review of hazard analysis and its incorporation into building codes, then discusses some current issues and developments. Examples are drawn from Canadian practice, with which I am most familiar, but the concepts apply broadly to other regions as well.

### Causes and Distribution of Seismic Hazard

Over 90% of the world's seismicity occurs within relatively narrow bands where two or more of the tectonic plates that make up the earth's lithosphere slide past or collide with each other. Within plate-margin regions, seismotectonic processes are relatively well understood. Strain energy is accumulated by the relative motion of the plates, and released by seismic slip along plate boundary faults. For crustal earthquakes (e.g. such as those along the San Andreas fault system), the faulting often ruptures the ground surface during large earthquakes. The magnitudes of observed earthquakes, their rupture dimensions and frequency of occurrence can be directly related to rates of slip and strain energy accumulation. This provides a valuable physical basis for interpreting seismicity.

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In regions far removed from plate boundaries, including most continental regions, seismicity tends to be more diffuse and infrequent. Nevertheless, large and damaging earthquakes do occur in mid-plate regions, as for example the devastating 2001 **M**7.7 Bhuj, India earthquake (where **M** is moment magnitude). The causative mechanisms of mid-plate earthquakes are often ambiguous. In general, earthquakes within stable continental interiors relieve long-term internal plate stresses that are driven by distant plate interactions. The locations where stresses are relieved are usually zones of weakness of large crustal extent, typically pre-existing faults left behind by older episodes of tectonism. Previously rifted or extended crust is believed to be of particular importance in localizing seismicity (Johnston et al., 1994). Because the earthquake-generation process is indirect, and potential zones of weakness are widespread, seismicity is often diffuse, occurring in broad regional zones rather than along narrow well-defined faults. The events may take place on a series of buried crustal faults, in locations that cannot be readily foreseen. Furthermore, mid-plate earthquakes do not often cause surface rupture. A global overview of large events in stable continental interiors (Johnston et al. 1994) revealed that of 452 earthquakes with **M**>5, including 17 events of **M**>7, there were only 7 cases of surface rupture. Even the **M**7.7 Bhuj, India earthquake did not cause surface rupture. In eastern North America, there is only one known case of surface rupture during an historic earthquake, that of the M6 1989 Ungava, Quebec earthquake (Adams et al., 1991). The lack of surface rupture makes geological investigations of mid-plate earthquake hazards very challenging. A further complicating factor is that faults in mid-plate regions may exhibit time-varying behavior, with periods of activity that last thousands or tens of thousands of years, interspersed with periods of inactivity that are an order of magnitude longer in duration (Crone et al., 2003).

Because it is not generally possible to delineate and characterize the causative structures of seismicity in a deterministic fashion, probabilistic analyses form the basis for seismic hazard analysis in most parts of the world. A shortcoming of hazard analyses in mid-plate regions, be they probabilistic or deterministic, is that potentially hazardous faults that have been quiescent in the last few thousand years may be difficult or even impossible to identify and characterize.

**The Basics of Seismic Hazard Analysis**

How has seismic hazard been accommodated in engineering design? The original impetus for inclusion of seismic provisions in building codes in North America was the engineering experience gained in the aftermath of the 1933 Long Beach, California earthquake. This earthquake served as a wake-up call to engineers: many schools, in particular, were damaged during the Long Beach event, and casualties would have been much heavier had the earthquake occurred while school was in session. A tradition has been established in which experience gained in significant earthquakes is incorporated into subsequent updates to the building codes.

Through the 1940s and 1950s, seismic design provisions in building codes tended to be based on qualitative evaluations of hazard. Later, quantitative seismic hazard maps based on probabilistic analysis were introduced. In Canada, for example, a major watershed for seismic design philosophy came in 1970 with the inclusion of the first national probabilistic seismic hazard map. This map was based on the work of Milne and Davenport (1969), who used extreme value statistics to calculate a gridded map of peak ground acceleration (PGA) having an annual exceedence probability of 0.01 (100 year return period). Under the assumption that earthquake arrivals are Poisson distributed, they wrote an expression for the largest shock amplitude experienced at a site per year, which has the form of a Type II extreme value distribution (Gumbel, 1954). They also developed a related amplitude recurrence method, based on counting the annual number of exceedences of a specified acceleration at a site. The inherent assumption was that, broadly, the past level of earthquake activity at a point is statistically representative of the future, and hence the recurrence times may be treated probabilistically.

Since the 1970s, seismic hazard maps have been developed for building code applications based on a probabilistic approach. Around the same time that Milne and Davenport (1969) were developing their seismic hazard maps of Canada, Cornell (1968) was developing a somewhat different methodology, which was coded into a FORTRAN algorithm by McGuire (1976). In the Cornell-McGuire method, the spatial distribution of earthquakes is described by seismic source zones, which may be either areas or faults. The source zones are defined based on seismotectonic information. An active fault is defined as a line source; geologic information may be used, in addition to historical seismicity, to constrain the sizes of events and their rates of occurrence on the fault. Areas of diffuse seismicity, where earthquakes are occurring on a poorly-understood network of buried faults, are represented as areal source zones (e.g. polygons in map view); historical seismicity is used to establish the rates of earthquake occurrence for earthquakes of different magnitudes. The exponential relation of Gutenberg and Richter (Richter, 1958), asymptotic to an upper-bound magnitude (Mx), is used to describe the magnitude recurrence statistics in most cases, although for specific faults a characteristic earthquake model (Schwartz and Coppersmith 1984) may be used. The upper magnitude bound for the recurrence relations, Mx, is a limit for integration in the hazard analysis, and represents the magnitude above which the probability of occurrence is 0. Mx values may be defined from geological information in the case of well-understood active faults. For areal source zones, Mx is usually based on the largest observed magnitudes in similar tectonic regions worldwide. The rationale for this approach is that the historical time period is too short to establish Mx empirically for any particular source zone; by using a global seismicity database for similar regions, we essentially substitute space for time in extending the seismicity database. Thus an Mx for unrifted mid-plate regions would be about **M**7, while Mx for rifted mid-plate regions such as the St. Lawrence Valley would be about **M**7.5, or even slightly larger (Johnston et al., 1994). The spatial distribution of earthquakes within each source is usually assumed to be random (i.e. uniformly distributed), although other treatments are possible.

Ground-motion relations provide the link between earthquake occurrence within a zone and ground shaking at a site. Ground-motion relations are equations specifying the median amplitude of a ground motion parameter, such as peak ground acceleration or response spectra, as a function of earthquake magnitude and distance; these relations also specify the distribution of ground motion amplitudes about the median value (i.e., variability). To compute the probability of exceeding a specified ground motion amplitude at a site, hazard contributions are integrated over all magnitudes and distances, for all source zones, according to the total probability theorem (in practice, sensible limits are placed on the integration range for computational efficiency). Thus the mean annual rate of exceeding a specific shaking level, *x*, at a site is:

$$\lambda(X \geq x) = \sum_{i=1}^{I} \upsilon_i \iint f_i(m) f_i(R \mid m) P(X \geq x \mid m, R)\, dR\, dm$$

where $\upsilon_i$ is the mean annual rate of the *i*th source, *m* is earthquake magnitude, *R* is the distance to the site, $f_i$ ( ) represents a probability density function, and *P* ( ) stands for the probability of the argument (Reiter, 1990). Calculations are performed for a number of ground motion amplitudes, and interpolation is used to find the ground motions associated with the chosen probability levels. The basic procedures are described by EERI Committee on Seismic Risk (1989), the U.S. National Research Council Panel on Seismic Hazard Analysis (1988), Reiter (1990) and SSHAC (1997). Because of its ability to incorporate both seismicity and geologic information, the Cornell-McGuire method quickly became widely used and popular in applications throughout the world. Its application to seismic zoning in Canada has been described by Basham et al. (1982, 1985), Adams et al. (1999), Adams and Halchuk (2003, 2004) and Adams and Atkinson (2003).

The ability to incorporate geologic information through the definition of seismic source zones appears to be a significant advance offered by the Cornell-McGuire method, as compared to the more statistically based methods pioneered by Milne and Davenport (1969). However, the amplitude recurrence distribution of Milne and Davenport (1969) and the Cornell (1968) method are actually rather similar. The division of a region into uniform zones of occurrence (as in the Cornell approach) is really a type of spatial smoothing that is applied before the numerical analysis is performed (Atkinson et al., 1982). If the data for the amplitude recurrence distribution analysis are smoothed over an identical area then the results of the two analyses should agree. The sequence and manner in which the data are smoothed appear to constitute the real difference between the two approaches.

There is an advantage to using the Cornell approach when zones of earthquake occurrence can be delineated on the basis of independent geological evidence. In this case the method has included important additional information that influences the seismic hazard. In most cases, however, the definition of the source zones is strongly influenced by the historical seismicity patterns; then, the definition of source zones is simply a smoothing over concentrations of seismicity.

The definition of source zones also suffers from being a highly subjective exercise. In the 1980s and 1990s the U.S. nuclear industry was struggling with the consequences of this problem as it aimed to reassess the seismic safety of existing nuclear power plants throughout the eastern United States. Teams of seismological consultants were tasked to develop a range of seismic source models to express the wide range of competing views. Through this process the role of uncertainty in interpretation of geological and tectonic data was illuminated, and its effects on seismic hazard results defined (EPRI, 1986). The essential question is: over what area(s) should seismicity be smoothed? What geologic information should be used to determine the extent of such smoothing? How do we evaluate whether a set of defined source zones is 'right' or even reasonable?

In view of these discussions, and the lack of a satisfactory resolution, the U.S. Geological Survey (Frankel et al., 1996) decided to develop a methodology for their national seismic hazard mapping program that would eliminate the need to define seismic source zones. Frankel's method is similar in concept to the smoothed amplitude recurrence method - although it is also different in some respects. Because of the difficulty of objectively defining seismic source zones, Frankel et al. (1996, 1999) chose to base the probabilistic amplitude calculations for regions far from identified active faults on smoothed historical seismicity, in which various scale lengths for the smoothing are considered. These scale lengths for the smoothing essentially take the place of seismogenic source zones.

At present, the Cornell-McGuire method is the most widely used method for site-specific analysis worldwide, and is used in the Canadian national seismic hazard maps (Basham et al. 1982; Adams et al. 1999). The problems involved in the subjective definition of source zones are addressed in the latest maps (Adams et al. 1999; Adams and Halchuk, 2003) by using a range of possible models to define the associated uncertainty. The smoothed seismicity method, in combination with the separate treatment of known active fault sources, is used in the U.S. national seismic hazard maps (Frankel et al. 1996, 1999). These differences in approach are partly responsible for some of the discrepancies observed in seismic hazard maps at the Canada-U.S. border (Halchuk and Adams, 1999). For site-specific analysis of critical facilities, the Cornell-McGuire approach, with a thorough treatment of uncertainties in all input parameters, is the most widely-used and accepted approach (eg. McGuire et al., 2002).

**An Informal Evaluation of How Far We've Come**

With significant advances in knowledge and methodology over the past few decades, as discussed in more detail in the next section, one might expect current seismic hazard maps to look very different from the first probabilistic seismic hazard maps produced decades ago. It is interesting to examine the extent to which our advances have influenced seismic zoning. As an illustration, I compare the most recent seismic zoning map for eastern Canada (Adams and Halchuk, 2003) to the equivalent map drawn by Milne and Davenport 30 years earlier. The current map was developed by the Geological Survey of Canada over the last 10 years or so (Adams et al. 1999; Halchuk and Adams, 1999). It is based on the Cornell-McGuire method, and maps 5%-damped pseudo-acceleration at selected periods, for a probability level of 2% in 50 years. It includes a relatively heavy weighting of geological factors believed to influence the likely locations of future large events. Figure 1 superimposes the latest seismic hazard results from these maps for eastern Canada, for a natural period of 0.2 seconds (from Adams et al., 1999), on the Milne and Davenport (1969) contours. I number the contours 1 through 4 to reflect the relative acceleration amplitudes associated with each contour, where each increase in 1 represents roughly a factor of two increase in amplitude (on both the Adams et al. and Milne and Davenport maps). The reason that relative amplitudes are plotted is that this is the best way to see the overall impact of the maps on seismic design levels. There are many differences in the plotted ground motion parameters and how they are implemented in the design process. A longer return period for the input parameters implies larger input ground motions, but these are balanced against other factors that are used to calculate the seismic loads (such as ductility factors by which to divide the loads, and so on). With each new seismic map development, there has been a tendency to 'calibrate' the code provisions back to a previous version. The calibrations have been based on the principle that the seismic forces should be equivalent, in an average way across the country, to those used in the previous version of the code (eg. Heidebrecht et al., 1983). (Note: specific changes are made as required to accommodate deficiencies in practice identified from engineering experience in earthquakes.) This ensures that the overall level of seismic protection, which is believed to be adequate on balance (though subject to refinement to correct identified deficiencies), is maintained. It also acknowledges that significant changes in the overall concepts of seismic design, which would cause a real change in level of protection, evolve over a longer time frame than do changes in the evaluated levels of ground motion for a stated probability. Thus the real importance of the seismic zoning maps in the design process, at least for building code applications, is in establishing *relative* levels of seismic ground motion.

Examining Figure 1, the similarities between the 1969 contours (dotted lines) and the 1999 contours (solid lines) are more striking than are the differences. In both cases, the region of highest hazard (4) is confined to the Charlevoix seismic zone, with the most recent maps indicating a more tightly-defined area of highest hazard. The newer maps feature smoother contours along the St. Lawrence, which result from smoothing the seismicity over broader geologic regions (in this case an ancient rifted margin). Moderate hazard (2 to 3) is indicated throughout the St. Lawrence and Ottawa valleys, with a consistent pocket of elevated hazard near the border of New Brunswick with Maine.

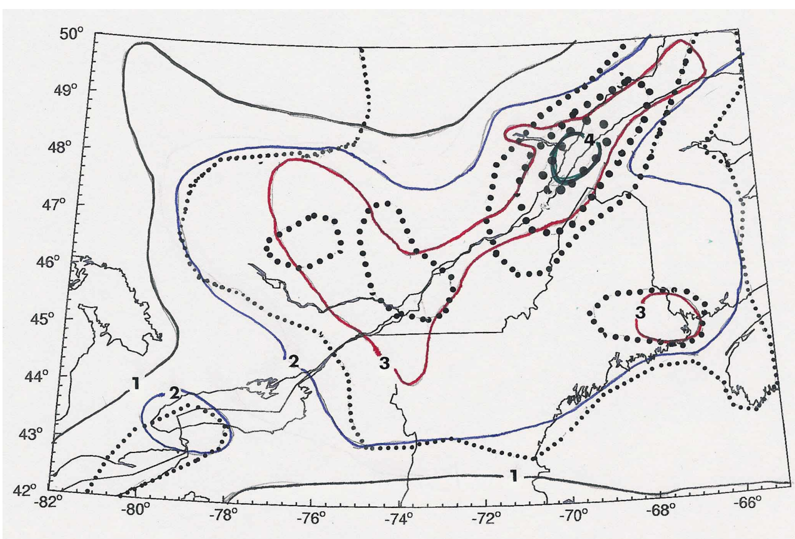


Figure 1. Comparison of seismic amplitude contours defined by Milne and Davenport (1969, dotted lines) to those defined by Adams and Halchuk (2003, solid lines). Contours have been renumbered 1 to 4 (solid lines correspond to 0.2 sec spectral acceleration of 16% g, 32% g, 60% g and 120% g, respectively, for a return period of 2500 years).

These maps, prepared 30 years apart, using different methods and different databases, reveal striking and persistent similarities, and differences that are not very marked. The reason for this can be appreciated by referring to the historical seismicity in the region, as plotted in Figure 2. Seismicity is concentrated in diffuse but reasonably well defined clusters: along the Ottawa and St. Lawrence valleys, near the New Brunswick-Maine border, and to a lesser extent near the western end of Lake Ontario. The largest historical events have been in the Charlevoix region. All of the seismic hazard maps of Canada, from 1970 to the present, strongly reflect these distributions. The more recent earthquake data indicate that some of these clusters are more tightly defined than was apparent from the older less precise data; hence the more recent maps feature tighter hazard contours in some areas. The underlying reality is that while methods and data have been refined, our overall understanding of seismic hazards in eastern Canada as applied to the National Building Code has not changed that much since the original work of Milne and Davenport (1969). While this example is specific to eastern Canada, the same general principle applies over many regions. Our seismic hazard zoning maps are a relatively simple and transparent consequence of the patterns of historical seismicity. What has improved over time is that we have refined our basic understanding of where and why earthquakes occur, and improved our characterization of the resulting ground motions and their probabilities. In the next section, I look at these advances in more detail, and then examine current shortcomings and future trends.

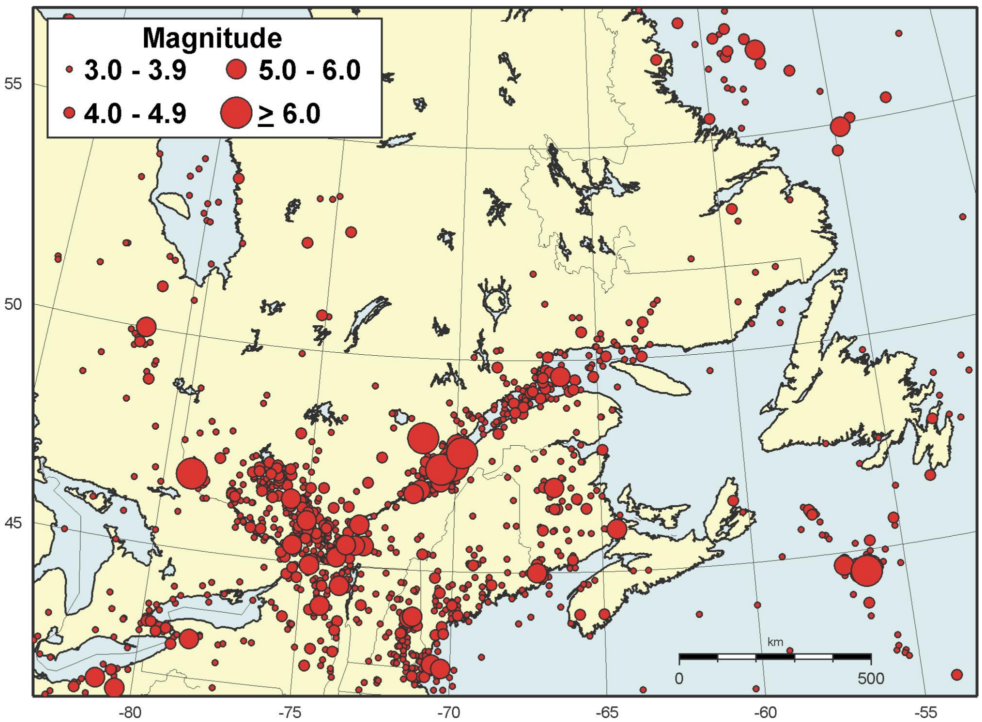


Figure 2. Historical seismicity of eastern Canada, from the Geological Survey of Canada (S. Halchuk). Note the correspondence between clusters of seismicity and areas of highest hazard shown on Figure 1.

## ADVANCES IN SEISMIC HAZARD ANALYSIS

A number of significant advances to seismic hazard analysis over the last 10 years or so are worth noting. The most helpful advances from a practical point of view have been the following.

**Resolution of some common misconceptions**

There are two common misconceptions that plagued probabilistic seismic hazard applications for decades. The first misconception hindered a well-reasoned trend to base seismic zoning maps and standards for critical structures on ground motion values having low probabilities. In typical North American building codes, earthquake design provisions in the 1970s were based on ground motions with a 100 year return period (0.01 per annum) – a relatively frequent occurrence. In the 1980s there was a shift to a 500 year return period (10% in 50 years). The latest codes, such as the National Building Code of Canada (as of 2005) and the NEHRP (National Earthquake Hazards Reduction Program) guidelines for building codes in the United States (from 1997 onwards), are based on a 2500 year return period (2% in 50 years). Ground motion probabilities for design of critical structures have likewise drifted downwards from about 5% in 50 years to values as low as 0.1% in 100 years. An argument often advanced against this trend is that low probability hazard estimates are an extrapolation of a short historical record: "100 years of data are extrapolated to return periods of thousands of years". In fact, the low probability of the calculated ground motions results from breaking the problem into component parts, where the result is the product of the components (U.S. National Research Council Panel on Seismic Hazard Analysis, 1988). It is the ground motion at a site that has a very low probability, not the event itself. For example, suppose we have a region that has experienced 10 potentially damaging (M>5) earthquakes in the last 100 years. Then the probability (per annum) of occurrence of an event of M>5 is 0.1. If a M>5 event occurs, we know from both regional and global recurrence models that the conditional probability of its magnitude being 6 or larger is about 0.1. Based on the total area of the subject region, the probability of the event being within 50 km of the site of interest is, say, 0.02. Finally, the probability of ground motions exceeding a certain target, given all of the above, is 0.5. The total probability of exceeding the ground motion target is thus the product $(0.1)(0.1)(0.02)(0.5) = 10^{-4}$, or a 'return period' of 10,000 years. The dominant factor that lowers the probability of damaging ground motions is the sparse spatial distribution of events; in this sense the low probability is more nearly an interpolation in space than an extrapolation in time. A growing recognition of this basic nature of low probability hazard analysis has improved our ability to utilize hazard analyses effectively to solve the engineering problems of interest – which necessarily involve design to rare earthquake ground motions rather than common occurrences.

Another misconception has revolved around the role of uncertainty. The results of seismic hazard analysis are subject to large uncertainty due to our limited knowledge of the component processes and large uncertainties in their interpretation; these uncertainties may become particularly pronounced at low probabilities. Because probabilistic hazard analyses are known to be subject to large uncertainty, there was a significant tendency to rely on a 'deterministic' approach to hazard, in which a design earthquake of a specified magnitude and location is used to determine the resulting ground motions. It is now widely understood, however, that uncertainty is inherent to the physical processes involved, and not specific to probabilistic analysis. Even in situations where the magnitude and locations of future earthquakes is indeed relatively deterministic (such as near a well-documented active fault), the ground motions remain uncertain. Thus deterministic analyses are subject to the same fundamental uncertainties as probabilistic analyses. They also suffer from the additional problem that nobody knows the likelihood of the determined outcome.

I do not mean to suggest that uncertainty is not an important limitation to seismic hazard analysis. Later in the paper, I will discuss some significant shortcomings in our understanding of uncertainty. However, uncertainty cannot be understood or mitigated by treating processes that are largely stochastic in nature as deterministic events. Uncertainty is a critical area of hazard analysis where major advances have been made, but which still requires much improvement in our understanding.

**Treatment of Uncertainty**

The proper treatment of uncertainty in hazard analysis is an area where significant advances have been made over the last decade. It has been recognized that it is important to distinguish between randomness in process (aleatory uncertainty) and uncertainty in knowledge (epistemic uncertainty) (McGuire and Toro 1986). Randomness is physical variability that is inherent to the unpredictable nature of future events, an example being the scatter of ground motion values about a median regression line. Randomness cannot be reduced by collecting additional information. Epistemic uncertainty arises from our incomplete knowledge of the physical mechanisms that control the random phenomena; it can be reduced by collecting additional information. This separation is clear-cut in principle, but in practice the distinction is somewhat arbitrary. Anderson et al. (2000) provide arguments that the epistemic uncertainty is in fact the dominant component, but is often cast instead as aleatory uncertainty, thus skewing hazard results. They point out that hazard maps at low probabilities would be significantly altered if the uncertainties were redistributed between aleatory and epistemic.

The seismic hazard maps developed for previous building codes (e.g. Basham et al. 1985) incorporated aleatory uncertainty (e.g. the variability in the ground motion relations), but were known to be sensitive to epistemic uncertainty. In recent years, a formal method of handling this uncertainty has been developed (McGuire and Toro, 1986; Toro and McGuire, 1987; McGuire et al., 2001), using a logic tree approach.

Each input variable to the analysis is represented by a discrete distribution of values, with subjective probabilities being used to describe the credibility of each possible assumption. Each possible combination of inputs produces a different output, so that a typical application of the process would produce thousands of possible results. The uncertainty in results can then be expressed by displaying a mean or median curve, and fractiles that show the confidence with which the estimates can be made (e.g. EPRI, 1986; Toro and McGuire, 1987; Bernreuter et al., 1985; McGuire, 1995). The use of a logic tree approach to investigate and quantify uncertainty in seismic hazard estimates is a significant advance in methodology that has been explored for some building code hazard maps (eg. Adams et al., 1999; Adams and Halchuk, 2003; Frankel et al., 1999) and is now widely used in site-specific analyses for critical structures throughout North America (eg. McGuire et al., 2001).

**Uniform Hazard Spectra**

Another major change in the methodology of specifying ground motions for use in engineering design involves the use of the 'uniform hazard spectrum'. In 1970s and into the 1980s, seismic hazard maps presented expected levels of peak ground acceleration (PGA), and sometimes peak ground velocity (PGV). Similarly, most standards for critical facilities were based on evaluation of PGA and/or PGV at that time. For engineering design, a much more useful description of ground motion is a response spectrum (typically PSA, the pseudoacceleration spectrum), which defines the response of a damped single-degree-of-freedom oscillator to an earthquake accelerogram, as a function of the oscillator's natural period. The response spectrum contains information about both the amplitude and frequency content of the ground motion, as well as indirect information regarding its duration. In the past, the response spectrum used for engineering design was constructed by scaling a standard spectral shape to the site-specific PGA and/or PGV (eg. Newmark and Hall, 1982). In the last 10 to 15 years, it has become standard seismological practice to instead develop a uniform hazard spectrum (UHS). The underlying probabilistic seismic hazard calculation is the same. However, in the UHS methodology, the hazard analysis computes expected response spectral ordinates for a number of oscillator periods (McGuire, 1977, 1995). This eliminates the need to use standard spectral shapes scaled to an index parameter such as PGA, thus providing a more site-specific description of the earthquake spectrum; it also ensures a uniform hazard level for all spectral periods. This has been a natural evolution of seismic hazard methodology, made possible by improved ground-motion relations for spectral parameters.

Uniform hazard spectra computations, coupled with abundant new ground-motion data, have revealed that the scaled-spectrum approach used in past codes overestimated response spectra for intermediate periods for some types of earthquakes by a very significant margin (Atkinson, 1991). This is because the standard spectral shape was a description of ground motions for earthquakes in California, within a limited magnitude and distance range. It is now well known that the shape of earthquake spectra is actually a function of magnitude and distance, and varies regionally (e.g. Atkinson and Boore, 1997). In recent seismic hazard maps and other applications, a UHS approach is routinely used to overcome previous shortcomings of the scaled-spectrum approach and more accurately describe the site-specific frequency content of the expected ground motions. This concept has been taken even further in applications that develop uniform reliability spectra, considering also the slope of the hazard curves at the probability levels of interest and the structural reliability goals (McGuire et al., 2002).

Figure 3 provides a typical UHS, for Toronto, Ontario, for a probability level of 0.0001 per annum, in which uncertainty is included by plotting various fractiles (this curve is adopted from studies of facilities nearby). Considering all modeled combinations of input parameters, 50% of the results lie below the median curve, while 84% of results lie below the 84$^{th}$ percentile curve. Thus, for example, we can be 84% confident that the true hazard curve lies below the 84$^{th}$ percentile. Note that the mean UHS, obtained by weighting each result by its probability of being the 'correct' model, is significantly higher than the median.

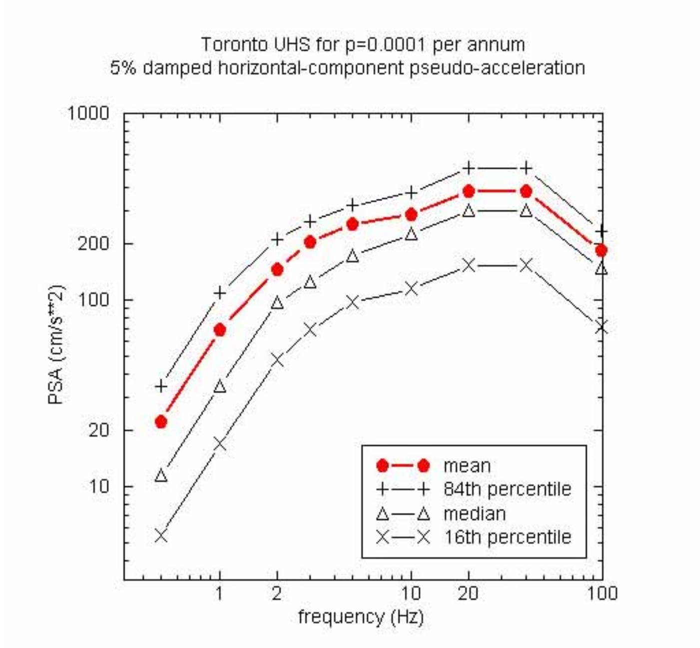


Figure 3 – Example Uniform Hazard Spectrum for Toronto for a probability of 0.0001 per annum, showing various fractiles of the results, representing epistemic uncertainty in the input parameters to the seismic hazard analysis.

**Lower Probability Level for Computations**

Another major trend in seismic hazard analysis is the lowering of the probability level for which the ground motion is being evaluated. Most modern codes are based on motions with a probability of 0.000404 per annum (2% in 50 years). This change was motivated by studies over the last 10 to 20 years that have shown that the best way to achieve uniform reliability across regions is by basing the seismic design on amplitudes that have a probability that is close to the target reliability level (eg. Whitman, 1990). The reason is that the slope of the hazard curve - the rate at which ground motion amplitudes increase as probability decreases - varies regionally. In active regions like California, ground motion amplitudes may grow relatively slowly as probability is lowered from 1/100 to 1/1000; this is because the 1/100 motion may already represent nearby earthquakes close to the maximum magnitude. In inactive regions, 1/100 motions are small, but grow steadily as the probability level is lowered. Thus there is no single 'factor of safety' that could be applied to motions calculated at, say, 1/100 per annum, that would provide design motions for a desired reliability of, say, 1/1000 per annum in both regions. The concept is illustrated in Figure 4. For uniform reliability across regions with differing seismic environments, the seismic hazard parameters on which the design is based should be calculated somewhere near the target reliability level. As discussed by Heidebrecht (2003), it is believed that this target level for seismic design of common structures corresponds to ground motions with a probability of about 2% in 50 years. For critical structures such as dams or nuclear power plants, the target probability level is even lower. In the latest seismic hazard maps of Canada (Adams and Halchuk, 2003) and the United States (Frankel et al. 1996, 1999; NEHRP 1997 to present), ground motions are calculated for an exceedence probability of 2% in 50 years.

The rationalization of probability level for hazard computations, driven by an understanding of the regional variability in the slope of ground motion versus probability and its implication for seismic design, has been a significant advance that should lead to safer structures in regions where large earthquakes happen only rarely. However, this change has been controversial, and not all agree that higher levels of seismic design are warranted in regions where earthquakes are relatively infrequent. For example, Stein et al. (2003) have argued that the use of 2% in 50 year probability motions in the U.S. national hazard maps have resulted in a situation whereby buildings in Memphis, Tennessee must effectively meet California seismic safety standards, despite the obvious differences in seismicity levels in the two regions. The arguments of Stein et al. (2003), and rebuttal by Frankel (2003), are a good example of this debate.

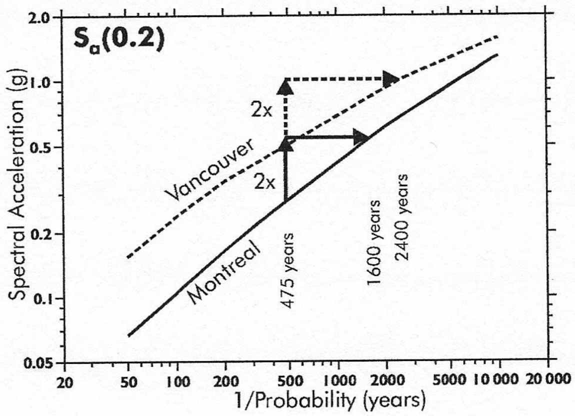


Figure 4 – The effect of different slopes of the ground-motion probability curve, from Adams and Halchuk (2003). Note that if a 1/475 (10% in 50 years) spectral acceleration (at a period of 0.2 s, for 5% damping) for Vancouver, B.C. (an active area) were multiplied by a 'safety factor' of 2, the resulting motion would have a probability of 1/2400. In Montreal (a less active area), the same exercise would result in a higher probability of 1/1600.

**Better Understanding and Definition of the Concept of "Design Earthquake"**

A useful exercise to understand the results of a probabilistic seismic hazard analysis is to 'deaggregate' the hazard. What the hazard analysis provides is an estimate of ground motion for a certain probability level. This ground motion represents a composite of contributions to hazard from earthquakes of all magnitudes at all distances (rather than a single design earthquake). By mathematically deaggregating the hazard, we evaluate the relative contributions of earthquakes of various magnitudes and distances to the calculated hazard. This allows the definition of one or more 'design earthquakes' that contribute strongly to hazard, and that will reproduce the calculated ground motions (McGuire, 1995). Such design earthquakes are useful in engineering applications. Figure 5 shows the results of a typical deaggregation, in this case for spectral acceleration (PSA, 5% damped horizontal component) with a natural period of 0.2 seconds, at Montreal, at the 2% in 50 year probability level. The PSA at a natural period of 0.2 seconds is a good engineering measure of the ground motion that a typical low-rise building would 'feel' during an earthquake. Figure 5 shows that the hazard at Montreal for this probability is dominated by earthquakes of about M6.5, occurring within 50 km of the city (see Halchuk and Adams, 2004).

Progress in understanding and evaluating appropriate 'design earthquakes' has been an important and practical advance. It has improved our ability to utilize the results of a hazard analysis to help engineers design and analyze structures with appropriate input ground motions – motions that are characteristic of the type of earthquakes that the structure might actually experience. No longer is every structure designed to a scaled version of the famous 1933 El Centro record. Instead, appropriate real records in the magnitude-distance range that contributes most to hazard may be selected from a large catalogue, if such records exist. If the records do not exist for the region of interest, they may be generated by a simulation methodology (eg. Atkinson and Beresnev, 1998, 2002; Saikia and Somerville, 1997; Hartzell et al., 1999). Alternatively, hybrid techniques may be used that combine the advantages of real recordings with the flexibility of simulation methodologies. For example, the amplitude spectrum for a desired magnitude, distance and site condition, as based on a seismological model, may be used in combination with the phase spectrum from a real recording (with some limits on the magnitude and distance to ensure a reasonable phase spectrum), in order to simulate a realistic time history (McGuire et al., 2001).

Advances in the understanding of the design earthquake concept are linked with advances in the treatment of uncertainty and the implementation of the UHS concept, to provide a powerful means of specifying design earthquake motions for important projects. The state-of-the-art in this regard is given in detail by McGuire et al. (2001, 2002). The development of seismic ground motions begins with a probabilistic seismic hazard analysis that draws from the current knowledge of earthquake sources, recurrence statistics and ground motion relations, according to the SSHAC (1997) methodology. This includes a thorough evaluation of all sources of epistemic uncertainty. The hazard analysis will result in response spectra over a broad range of frequencies (eg. 0.2 to 100 Hz) and a wide probability range (eg. $10^{-2}$ to $10^{-5}$ per annum). Deaggregation is then performed on the mean hazard for the target probability level, by both magnitude and distance, to determine the relative hazard contributions at 1 and 10 Hz. If multiple ground motion relations have been used to characterize epistemic uncertainty, then the deaggregation may be done with each of these, weighted by the subjective probabilities that are used in the hazard analysis. McGuire et al. (2001) developed a catalogue of time histories categorized by magnitude, distance and site condition, to use in developing appropriate time histories to match the target spectra for the design events identified by the deaggregation. They also provided detailed procedures that can be used to ensure that the developed time histories match the target spectra in a rigorous way. An example application of these procedures for both typical eastern and western North American sites is given in McGuire et al. (2002).

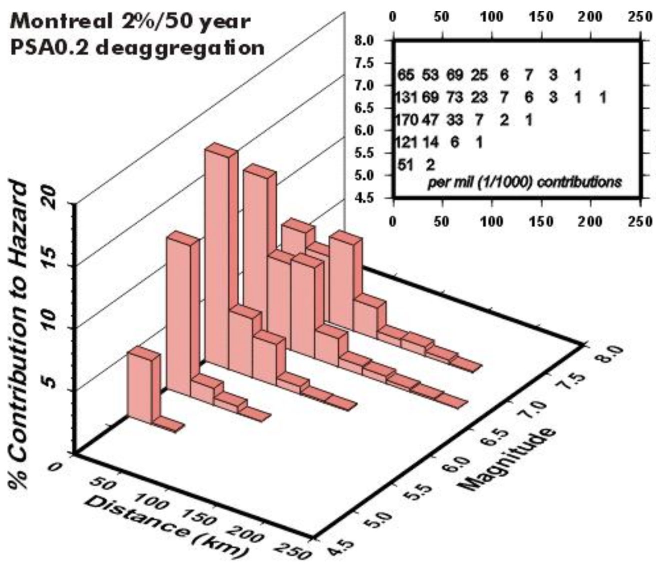


Figure 5 - Hazard deaggregation for 2%/50 years median PSA(0.2sec) at Montreal, from Adams and Halchuk (2003).

**Better Understanding of Earthquake Ground Motion Processes**

Over the last 5 to 10 years, there has been a remarkable increase in recorded ground-motion data from earthquakes in all parts of North America, and from earthquakes in Japan and Taiwan. The ground-motion database has improved due to a combination of developments in seismometry and increased deployments of instruments. In well-instrumented regions like Japan, Taiwan and California there are now thousands of available strong-motion recordings. From these, we can develop a much better empirical characterization of ground motion generation and propagation. We can determine the distribution of slip on faults, and characterize factors that profoundly influence ground motion, such as directivity, near-fault displacements, and basin effects (e.g. Graves et al., 1998; Somerville et al., 1997). We can develop more robust empirical relations that are based on thousands of recordings (eg. Boore et al., 1997; Atkinson and Boore, 2003). Even in regions where strong-motion and seismographic networks are relatively sparse, there are now thousands of useful recordings, although most of these are for small-to-moderate events at fairly large distances. These records, coupled with advancements in ground-motion modeling techniques (e.g. Pitarka et al., 2000; Beresnev and Atkinson, 2002), are improving our ability to understand and model ground-motion processes, and will ultimately lead to refinements in future hazard evaluations. On the other hand, many puzzles still remain. For example, the well-recorded 1999 Chi-Chi Taiwan earthquake resulted in ground motions that were much larger than would be predicted based on previous observations (Boore, 2001), while the 1988 Saguenay, Quebec earthquake resulted in ground motions much larger than would be predicted based on previous observations (Atkinson and Boore, 1998). As yet, we do not really understand whether 'anomalous' earthquakes are truly anomalous, or simply misunderstood in the context of our present models and approaches. Furthermore, we have not come to grips with complicating factors like the potential for highly asymmetric ground motions, such as on the hanging wall versus the footwall of thrust faults (Anderson et al., 2000).

Finally, with more seismic instrumentation and analyses, our understanding of seismicity patterns and magnitude recurrence statistics has gradually evolved over time, improving our understanding of seismic hazard.

## DISCUSSION

### Shortcomings in Application of Seismic Hazard Analysis

One area in which much progress remains to be made is in how we fully characterize and utilize uncertainty, given that we don't know all of the relevant parameters. As pointed out by Field et al. (2003), to ensure a stable hazard analysis process, we would ideally like to start by identifying all viable hypotheses and including them in an initial hazard model. Over time, as models are rejected, they could be removed from the full range of options. Under this approach, hazard analyses might not change dramatically over time, in contrast to the case in which we start with only a few well-known models, than add new models as new information emerges. However, such an ideal approach presupposes that we can identify all viable hypotheses at this time, which seems unlikely. As a cautionary tale, Field et al. (2003) point to an apparent paradox: in southern California, one of the most data-rich regions in the world for seismic hazard analysis, the multiple forecasts generated by the activities of a large working group in that area (Field et al., 2000 and papers therein) appear to show that, after extensive study, hazard estimates are more uncertain than previously thought. In other words, a larger amount of study of uncertainty led to a larger apparent uncertainty. To cite a specific example, even if we obtain further information on site characteristics by determining the shear-wave velocity profiles of all sites, we apparently do not significantly reduce uncertainty in site response (Field et al., 2000). There are significant other pieces of evidence, notably the precarious rock studies of Brune (1996, 2001), that also suggest that we may not understand the actual influence of uncertainty on seismic hazard.

The underlying problem is that a lack of knowledge is, by its very nature, not amenable to accurate quantification. Current probabilistic seismic hazard analysis (PSHA) does its best by trying to capture some of the obvious culprits, but we may be fooling ourselves into thinking we know more than we really do. I will illustrate this point using examples from seismic hazard analysis in Canada, but the concept is general and any number of examples could be drawn.

The first example deals with how uncertainty in seismic source models in eastern Canada is handled at present in the national seismic hazard maps, presented by Adams and Halchuk (2003). The national hazard maps aim to make an estimate of uncertainty in source models by considering two 'end members' of a family of models. One end member assumes that future earthquakes will be concentrated in areas of past historical seismicity (the H model). The other end member asserts that the risk of large earthquakes should be considered uniform over a broad series of faults along the St. Lawrence, Saguenay and Ottawa Valleys that formed several hundred million years ago during early attempts to open the Atlantic Ocean. The argument is that these deep-seated rift faults are believed to be potential sources of weakness that could be reactivated by the current high horizontal compressive stress field. Several investigators have shown that large earthquakes in eastern North America occur preferentially within such zones (Kumarapelli and Saull, 1966; Adams and Basham, 1989; Johnston et al., 1994; Adams et al., 1999). Global studies indicate that, within stable continental interiors, 70% of earthquakes of **M**>5 and all events of **M**>7 occur within such rift zones (Johnston et al., 1994). Current seismic hazard evaluations for eastern Canada draw heavily on this concept. To capture this possibility, an alternative model (the R model) was drawn to encompass such rift fault features. Figure 6 shows the two models.

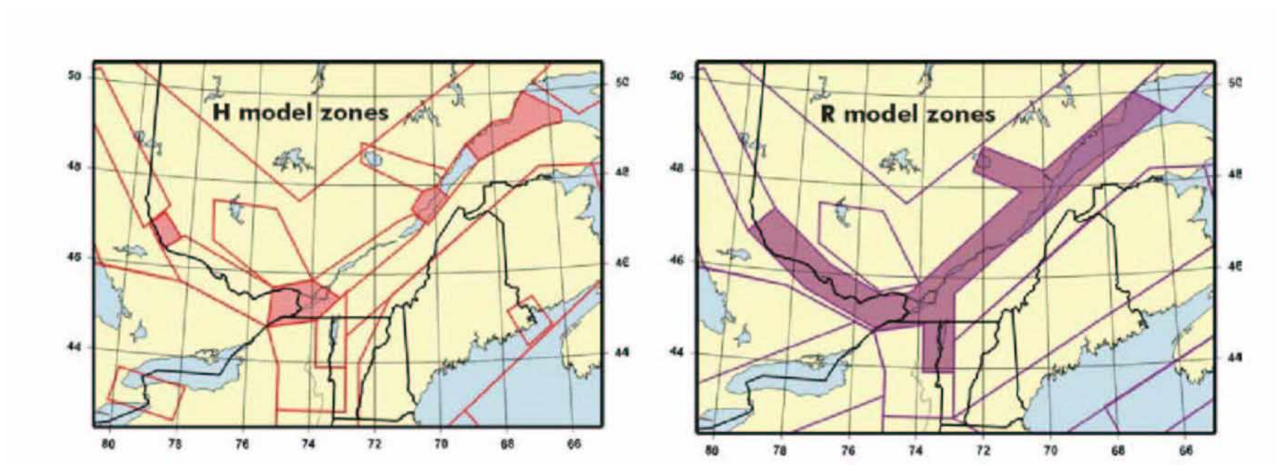


Figure 6 – H and R models for eastern Canada (Adams and Halchuk, 2003). In the H model, seismicity is concentrated in the red zones, while in the R model it is smoothed over the larger purple zone.

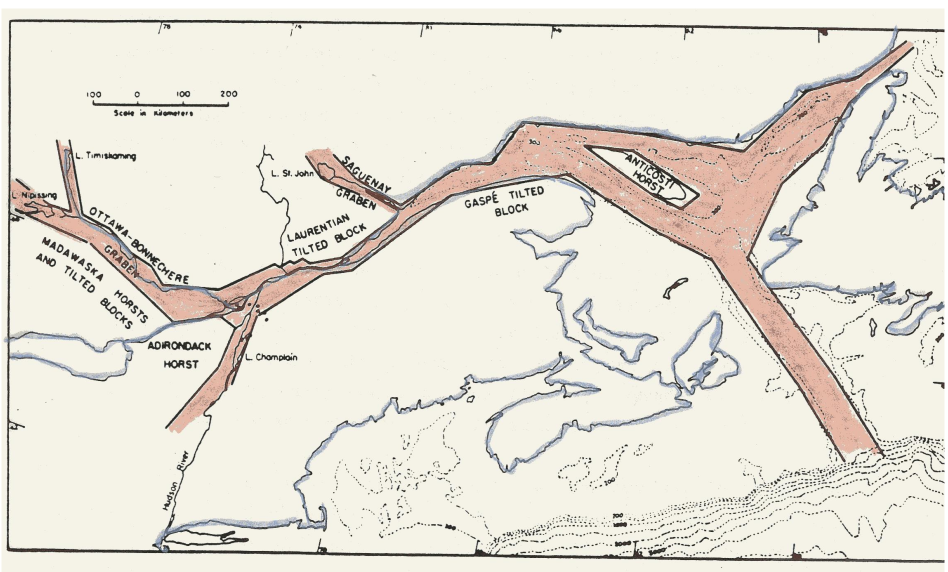


Figure 7 – Rifted areas of eastern North America, according to Kumarapeli and Saull (1966).

The idea is fine in concept, but the definition of the geologic zones is inevitably biased by past seismicity patterns, and thus less complete than it first appears. Figure 7 shows the original definition of rifted areas based on the geologic work of Kumarapeli and Saull (1966). Note that the rifted areas extend up the Saguenay Graben, down Lake Champlain, and also west from the Ottawa Valley, past Lake Nipissing. The original definition of the R model of seismicity, by Adams and Basham (1989), considered this information but was also influenced by contemporary seismicity. Thus their original concept, shown in Figure 8, did not include the failed arm that extends up the Saguenay graben, because as of 1988 when the model was drawn, this arm was dormant and did not appear to be all that significant. This arm was added to the model after the occurrence of the 1988 Saguenay earthquake, despite previous knowledge of the rift features. Ironically, the original version was proposed in 1988 and was published just after the Saguenay earthquake occurred (Adams and Basham, 1989). A speculative arm west through Lake Ontario was proposed in the 1989 version based on a weak seismicity trend. It did not have a geologic basis in the Kumarapeli and Saull model, but was proposed based on observations of some post-Ordovician faulting that appeared similar in age and style to the Ottawa-St. Lawrence-Champlain faulting, though different in scale, and by other work by Woolard concerning an arc of seismicity extending from the St. Lawrence through New Madrid (Adams, J., pers. comm., 2004). Similarly, the extent of the current zone shown in Figure 6 is open to question. A westward extension of the rift past Lake Nipissing was not drawn in the current model due to the lack of seismicity extending from North Bay to Sudbury, and a view that the geologic basis was weak (Adams, J., pers. comm.., 2004). Such an inclusion would increase the ground motion levels at locations such as Sudbury, Ontario by about a factor of three (based on a rough calculation). Other factors were also considered. For example, it was felt undesirable to spread the rift model out over too large an area (such as across southern Labrador), because this would dilute the hazard elsewhere (Adams, J., pers. comm.., 2004). Presumably, if the next big eastern earthquake is in one of these excluded regions, future versions of this model will be revised. In the meantime, however, is it fair to say we are capturing uncertainty in seismotectonics through our ‘end member’ models? And what about other possible explanations for features controlling seismicity, about which we know too little to warrant delineating models?

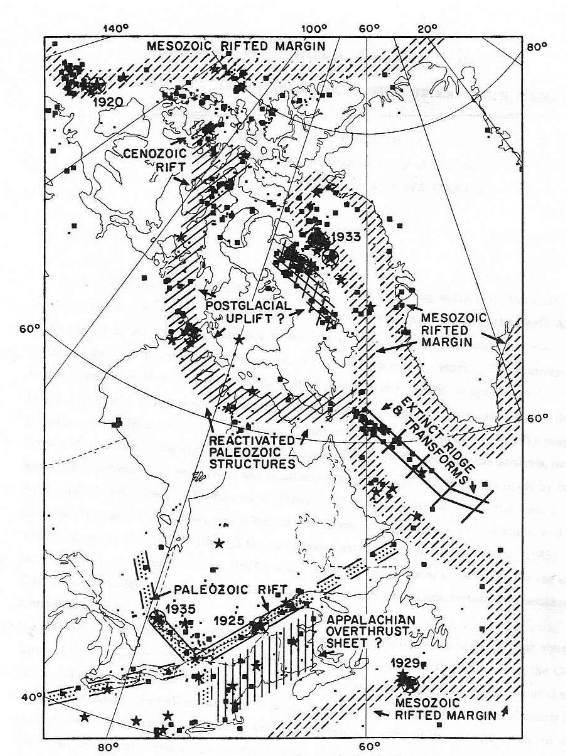


Figure 8 – Earthquakes of eastern Canada (M>3 since 1970; M>4 since 1960; M>5 since 1940; M>6 since 1900) together with an interpretative framework for the cause of the seismicity proposed by Adams and Basham (1989), then later revised as per Figure 6.

Another example of the difficulty of capturing uncertainty in an unbiased way concerns the impact that more information, as opposed to more interpretation, has upon seismic hazard analysis. It has become standard practice to expend significant resources on quantifying uncertainty, through delineating many possible models based on the same underlying information. Sometimes this process can be useful. For example, in the eastern Canadian case just described, additional models could be used to capture at least some of the uncertainties discussed. In other cases, however, it would be more fruitful to expend the available resources on actually collecting information that would reduce uncertainty.

An example of this point is drawn from hazard analyses for the Canadian national seismic hazard maps for the Lower Mainland Region of British Columbia, in which Vancouver is situated. Figure 9 shows a significant source of uncertainty for the shallow crustal earthquakes in this region as reflected in the current hazard maps (Adams and Halchuk, 2003). This uncertainty arises from the apparently anomalous nature of the magnitude recurrence relation for the region, as defined from seismicity to 1991. The magnitude recurrence relation suggests a mismatch between the relatively low observed rates of seismicity for small-to-moderate earthquakes, and the relatively high rates observed for large earthquakes. The observed rates do not agree well with a standard Gutenberg-Richter straight line relation (which should typically be a well-behaved straight line in Log N(M) vs. M, with a slope near 0.8). (Note: this relationship might look like a candidate for a characteristic earthquake model, but the source is a broad zone, rather than an individual fault.) The 2003

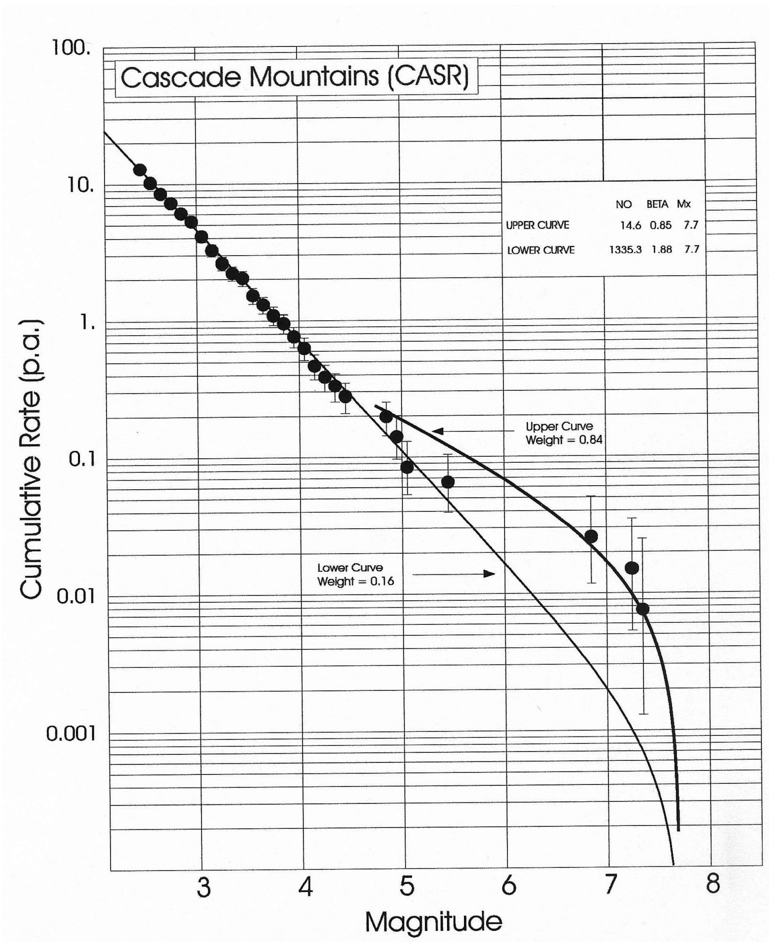


Figure 9 – Magnitude-recurrence data and curves for CASR, the shallow crustal source for the Strait of Georgia-Puget Sound region. The 2003 national hazard maps consider the lower curve, consistent with the apparent low-level seismicity, with a weight of 0.16, and the more conservative upper curve, consistent with the apparent large-magnitude seismicity, with a weight of 0.84. The curves were developed from historical seismicity to 1991, under the assumption that ML = **M**. From Adams and Halchuk (2003).

hazard maps have dealt with this problem by defining a broad range of possible recurrence relations for the zone, including a very wide range of recurrence slopes (b-value) from 0.37 to 0.82. The upper curve is given a weight of 0.84.

In this case, however, new information may resolve the problems posed by this poorly-behaved relationship. The 2003 maps are based on seismicity catalogues up to 1991, which contain a mixture of magnitude types, including some intensity-based or surface-wave estimates of magnitude for the large historical earthquakes, and ML (local magnitude), mb (body-wave magnitude), or Mc (coda magnitude) for the small-to-moderate events. Due to a lack of information at the time the maps were prepared, an assumption was made that all of the reported magnitudes are roughly equivalent to moment magnitude. With new information gathered over the last 10 years, it now appears that this was not a good assumption. From a variety of studies, there are new relations linking each of these scales to moment magnitude. In particular, the Geological Survey of Canada has obtained hundreds of moment tensor solutions for earthquakes that have occurred in western Canada since 1995 (Ristau et al., 2003), from which it is now possible to obtain a more definitive relationship between local magnitudes in the catalogue and moment magnitudes, for various regions of western Canada.

Ristau et al. (2003) and Atkinson and McCartney (2004) have shown that **M** exceeds ML for offshore events within the region by an average of 0.6 magnitude units. Cassidy et al. (2003) and Atkinson and McCartney (2004) find that **M**=ML for continental events. Atkinson and McCartney (2004) have examined, as a subset of these regional data, onshore events in southwestern B.C. within and below the CASR zone. It appears that for these events **M** = ML + 0.6. There is significant uncertainty in this relationship, as there are only about a dozen events within the geographic area defined by the CASR zone that have moment magnitude determinations, and many of these actually lie in the subducting plate (below CASR). The few shallow events in CASR with moment solutions appear consistent with the relation **M** = ML + 0.6; however it is possible that, with the collection of more data, events in the crust will eventually be shown to follow the continental relation of **M** = ML. On the one hand, signals from all events within and beneath CASR pass through the CASR crust on their way to the stations. On the other hand, the events in the underlying plate may have source characteristics more like the oceanic events than the continental events, and this may be a more important factor. Two alternative relations between **M** and ML are therefore credible: **M** = ML + 0.6 or **M** = ML. This discrepancy in magnitude scales represents a major potential bias in recurrence relations. More data are clearly crucial to defining the magnitude recurrence relation with confidence.

It is interesting to look at the implications of the provisional relationship **M** = ML +0.6 or **M** = ML for southwestern B.C. In this exercise, we must also consider other developments in magnitude estimates that impact the recurrence relation. Special studies of large historical earthquakes in B.C. (Rogers and Hasegawa, 1978; Cassidy et al., 1988; Bakun et al., 2002) provide more accurate estimates of moment magnitude for some of the largest events, while there are new empirical relationships between mb and moment, and Mc and moment. By recasting the magnitude recurrence relation for CASR in terms of moment magnitude for all events, and including the last 10 years of historical seismicity, we obtain the two alternative magnitude recurrence relations for southwestern B.C. shown on Figure 10 (Atkinson and McCartney, 2004) (corresponding to the two alternative relations between **M** and ML).

From Figure 10 it appears that there is no significant deviation from a Gutenberg Richter relationship in southwestern B.C. The data (**M**≥3) are fit by simple least-squares to the relation log N = 3.21– 0.74 **M** for the relation **M** = ML+0.6, or log N = 2.49 – 0.65 **M** for the relation **M** = ML**.** The uncertainty in the slope is relatively small compared to the previous range that suggested an uncertainty of more than 0.4. The new relations are not inconsistent with the upper curve (given a weight of 0.84) in the magnitude range over which the hazard was computed (4.75 to 7.7), but indicate that the lower curve (given weight of 0.16) is not credible for **M**≥6. This suggests that the analysts were able to arrive at a reasonable solution for the 'best estimate' given the contradictory information on hand; they instinctively focused on the apparent rates for large historical events. But they were unable to do much with the uncertainty. The same incomplete information that led to the apparent uncertainty limited the ability to interpret it.

New information affects other parameters in the maps too. For example, there are also new ground-motion relations for subduction-zone earthquakes in the region (Atkinson and Boore, 2003), and more detailed calculations of the motions expected from mega-thrust earthquakes on the Cascadia subduction zone (Atkinson and Beresnev, 1998). There are also indications that the ground-motion relations assumed for crustal earthquakes in B.C. may be conservative (Atkinson and Boore, 1997). Much of this new information lies outside of the previously-calculated uncertainty bounds for the parameters in question, because the results of various studies could not be anticipated. It would be premature to draw any conclusions as to whether the hazard map values presented for Vancouver are conservative or not. The point is that new information has the potential to greatly change our evaluation of seismic hazard, and the revised parameters may lie far outside what we had calculated as their uncertainty bounds. When looking at Figure 10, I conclude that the uncertainty indicated by the differences between the red and blue lines should be resolved by analysis of seismograms, rather than simply quantified. This is certainly feasible, although effort must be expended to determine more moment magnitudes for historical events within CASR.

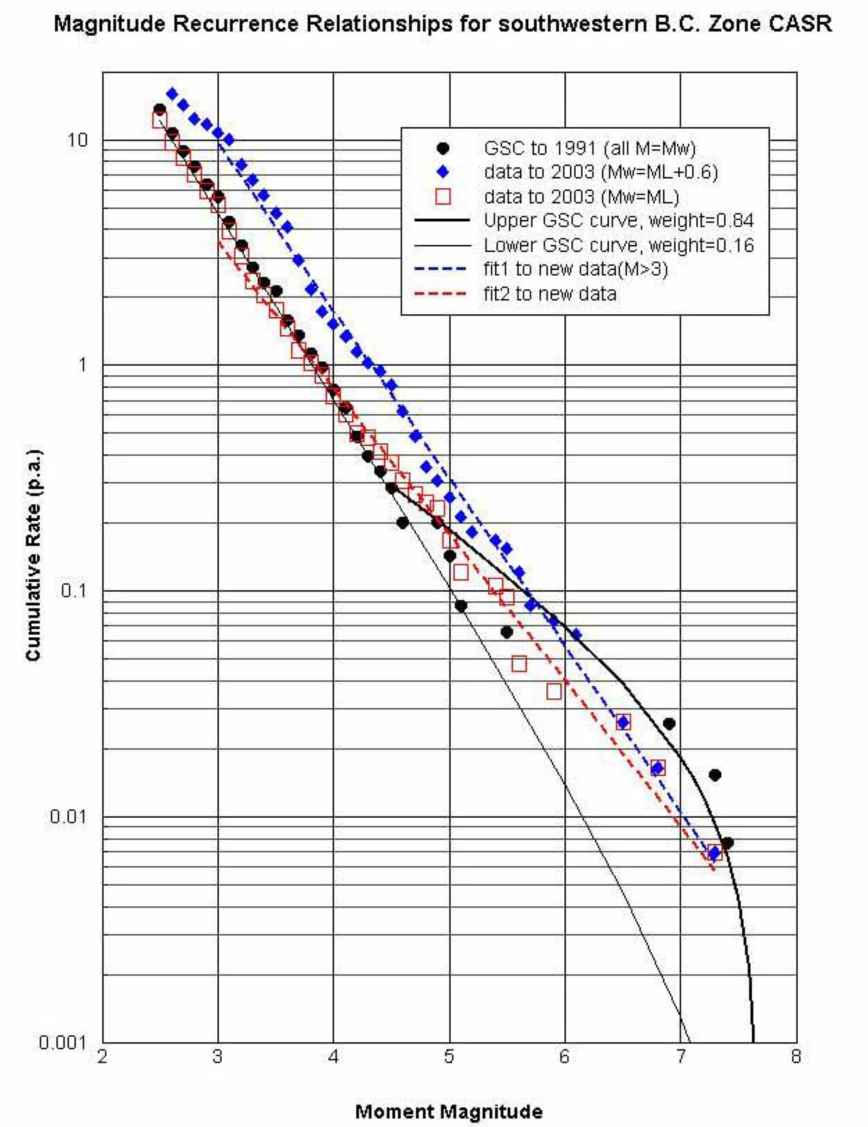


Figure 10 – Revised magnitude-recurrence relation for zone CASR, using a consistent moment magnitude scale for all events through 2003. Two alternative relations between moment M and ML are considered (Mw=ML+0.6 and Mw=ML). The GSC magnitude-recurrence relations and data rates from Figure 9 are also plotted for comparison. From Atkinson and McCartney (2004).

These examples are not presented as a critique of the work that has been done for the 2005 seismic hazard maps (which I endorse), but rather to illustrate our inability to accurately capture uncertainty. The same factors that create epistemic uncertainty also limit our ability to characterize it. This is a fundamental limitation with the evaluation of uncertainty that cannot be easily redressed. It should be recognized, then, that analyses of uncertainty, though useful, are inherently limited in their scope. I suspect that uncertainty is most often understated, because we can't model tomorrow's surprises. However, as we saw in the example shown above, uncertainty may also be overestimated.

Since the mean hazard curves are partly a function of the amount of uncertainty, it would appear to follow that mean hazard is underestimated if there is a tendency to underestimate uncertainty. On the other hand, the proposition that the mean hazard is indeed raised by the effects of uncertainty may not be entirely justified. For example, Brune (1996) found that the distribution of precarious rocks in southern California is not consistent with the large mean values of ground motions predicted by PSHA studies. However the distribution of these rocks appear to be consistent with hazard maps of Wesnousky (1986), that use only the median value for attenuation of peak ground motion, thus ignoring even the aleatory uncertainty (Anderson et al., 2000). The question is raised as to what is the appropriate role of uncertainty in forming seismic hazard estimates (Anderson et al., 2000). In my view, this question has not been adequately answered.

For reasons such as those discussed above, the median is sometimes suggested as an alternative to the mean; the median is inherently more stable with respect to the influence of uncertainty and will change less over time as our uncertainty changes. This was a key factor in the decision to base the seismic hazard maps of Canada on the median, for example (Adams, J., pers. comm.., 2004). However, this is not an ideal solution either, as the median is not the expected value. Moreover, as the median is significantly less than the mean (sometimes by a factor of 2), it potentially underestimates the true hazard if we believe that our uncertainties are indeed real. Thus there are significant outstanding issues in seismic hazard analysis with respect to the complete characterization and utilization of estimates of uncertainty. At the present time, I believe that resources are more appropriately expended on fundamental studies and data analyses that will actually reduce uncertainty, as opposed to exercises that aim to quantify and utilize it. For every dollar that is spent trying to quantify uncertainty, we should spend 10 dollars collecting and analyzing data that would reduce uncertainty.

## Future Trends in Seismic Hazard Analysis

*Real-time hazard information*

Ground motion data can now be accessed and analyzed even before earthquake shaking stops, leading to a new frontier in the area of real-time hazard information. The idea behind real-time seismic hazard information is simple. Ground-motion information is processed automatically, then sent to emergency management agencies and operators of critical structures and facilities. The TriNet project of southern California has demonstrated that it is possible to provide reliable information on the distribution of the intensity of ground shaking within a few minutes of the occurrence of an earthquake (Wald et al., 1999). California utilities have formulated detailed earthquake-response plans, in which the response actions are keyed to the data provided by the shake maps. Future developments may even allow warnings to be issued several seconds in advance of the most severe portion of the seismic shaking, allowing automatic safe shutdown of critical systems, such as those in nuclear power plants for example. Real-time spatial analysis of earthquake ground motion in densely populated regions can provide crucial and timely information to emergency response organizations and operators of critical industrial facilities, allowing them to prioritize their responses and take appropriate measures to reduce loss of life and mitigate damage. These systems are currently being implemented in a wide range of environments around the world.

*Better integration of multi-disciplinary hazard information*

Seismic hazard analysis has matured during the last 30 years of research and development. To go even further, it has been suggested by a working group in southern California that the next step is to replace generic ground motion equations with more detailed models based on the physics of wave propagation (see Field et al., 2000 and papers therein). The National Research Council (2003) asserts that future progress in PSHA will depend on earthquake system science to capture knowledge from a range of disciplines including seismology, geology, geodesy, rock mechanics and engineering. Such an integration of various observational disciplines will require new tools and new computational infrastructure to successfully implement. Field et al. (2003) point out that, at present, it is difficult to effectively evaluate the hazard implications of a wide range of potential rupture forecast methodologies, without custom hard-wired reprogramming of existing PSHA codes for each new methodology. They suggest that we need to build a flexible hazard infrastructure, which they term 'Open Seismic Hazard Analysis'. In such an infrastructure, any earthquake rupture forecast model, or any other type of PSHA component, could be 'plugged in' for analysis without change to the basic infrastructure. The software would be open-source and freely available, as described in the organizational website (http://www.OpenSHA.org). The concept is that OpenSHA would encompass virtually all types of seismic hazard analysis, including deterministic analyses where the occurrence of an event is presumed rather than assigned a probability. The development of a flexible, open, standard code for seismic hazard analysis would represent a major advance and contribution. Developing such an ambitious infrastructure will be a complex task, built over many years, but may ultimately revolutionize the way hazard analysis is conducted in the future.


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