# SEISMIC HAZARD ANALYSIS IN CANADA: AN OVERVIEW

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Abstract

This paper overviews developments in seismic hazard analysis in Canada, providing a review of the causes and distribution of hazard, a historical overview of hazard analysis, and comments on current issues and new developments. In the 30 years since the advent of seismic hazard analysis in Canada, methods and data have been refined, but our overall understanding of seismic hazards in most of Canada as applied to the national building code 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. 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.

Résumé

Cette étude est un comptage des dévelopments au sujet des calculs de risque séismiques au Canada, y inclue un révue des causes et la distribution des risques, un comptage des calculs de risques historiques, et des points d'observations au sujet des questions contemporaire et des dévelopments récent. Durant les dernière 30 années, depuis le début des calculs de risques séismiques au Canada, les méthodes et les données sont plus précies, may la compréhension des risques séismiques pour la majorité du Canada en réference de la Code National du bâtiment ne s'est pas modifié. Les cartes séismique de risques du Canada sont un conséquence simple et evident des patrons d'activité séismique historiques. L'amèlioration de la compréhension de 'ou' et 'pourquoi' les tremblements de terre ont arrivés est evident au court de temps. Notre characterization des données séismiques et leur probabilités ont aussi amèliorés. A l'instant, nouveaux données séismiques, disponibles presque au même moment, permet meilleure compréhension du production et propagation séismique et commence la fondament pour un système d'information de risques séismiques au même moment.

## 1. INTRODUCTION

Seismic hazard analysis has been an element of good engineering design practice in Canada for many decades; it is an integral component of the National Building Code of Canada (NBCC) and Canadian standards for design of critical structures such as dams, offshore structures and nuclear power plants. This overview of seismic hazard analysis in Canada begins with a summary of the causes and distribution of seismic hazard in Canada, provides an historical review of the treatment of hazard in the building code, and overviews some current issues and developments.

## 2. CAUSES AND DISTRIBUTION OF SEISMIC HAZARD IN CANADA

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, such as Canada's west coast, 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.

In regions far removed from plate boundaries, including most of Canada, 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 M7.7 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. 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 M7.7 Bhuj, India

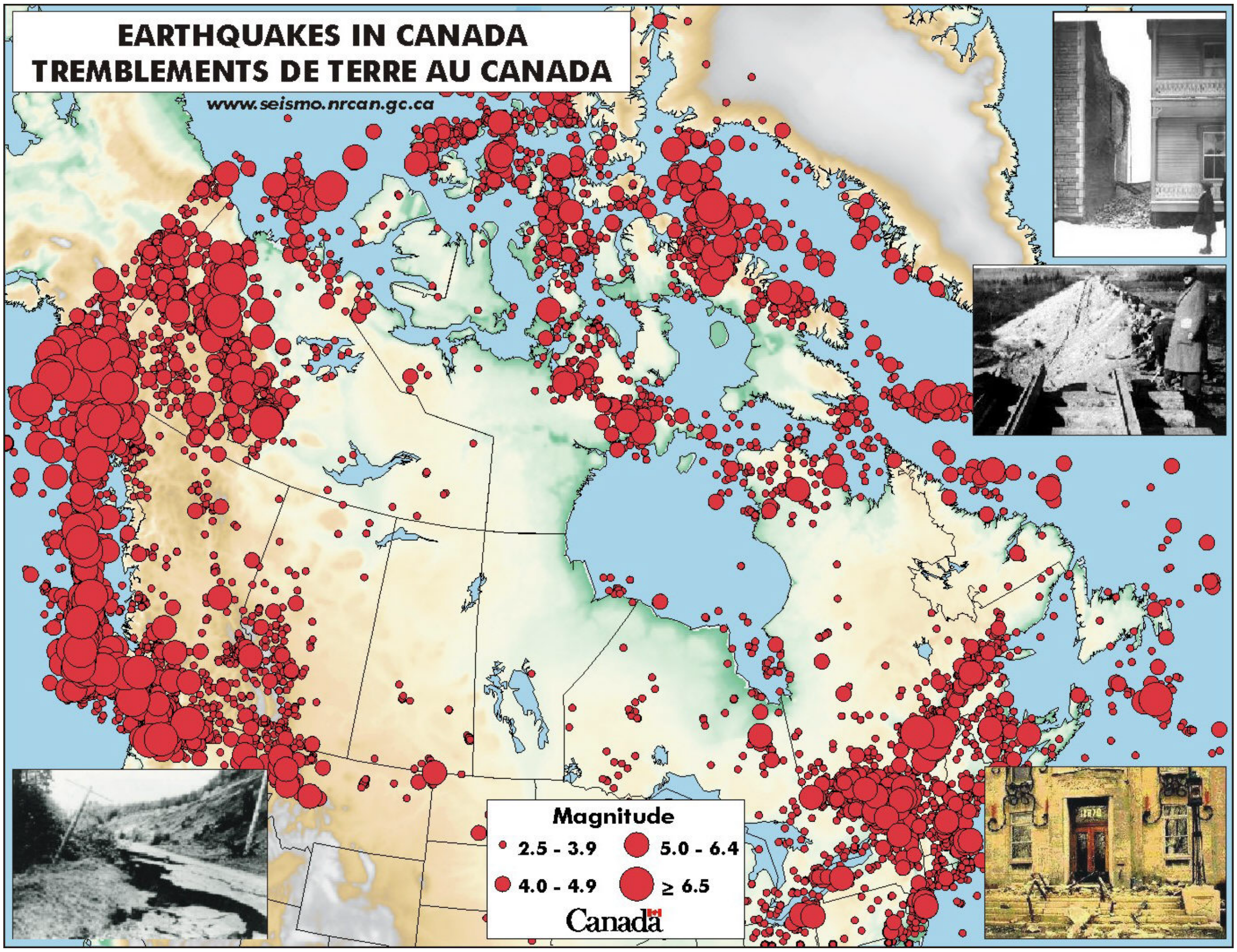


Figure 1. Historical seismicity of Canada, as plotted by the Geological Survey of Canada (www.seismo.nrcan.gc.ca).

earthquake did not cause surface rupture. In eastern Canada, 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.

### 2.1 Overview of Canadian Seismicity

Figure 1 shows the locations of historical earthquakes in Canada, as plotted by the Geological Survey of Canada. Figure 2 shows the tectonic elements of western Canada, the only region of Canada that is characterized by active plate-margin tectonics. The most prominent western plate boundary fault is the Queen Charlotte fault, a major strike-slip fault that marks the boundary between the Pacific and North American plates. One of North America's largest historical earthquakes, the M8.1 event of 1949, occurred along this fault. The other major plate boundary in western Canada is the subduction zone beneath Vancouver Island and Washington State, where the Juan de Fuca plate is being subducted beneath the North American plate. Geologic evidence suggests that great earthquakes (as large as M9) occur along the subduction interface with a mean recurrence interval of about 600 ±170 years (Adams 1990); the last great event happened 300 years ago, in 1700 A.D. (Satake et al. 1996). The subducting plate boundary is currently locked (e.g. there is no seismicity observed along the interface), accumulating strain for the next great earthquake. However, moderate earthquakes, such as the 2001 M6.8 Nisqually, Washington earthquake, occur relatively frequently within the subducting slab itself. Because of the active convergence of plates in this region, crustal faults are also seismically active, though not well mapped or understood. It is only recently that some of these active crustal faults are being imaged through improved event location techniques (e.g. Cassidy et al., 2000); much work remains to be done in identifying and understanding crustal faults in western Canada. In summary, then, the west coast region of Canada is subject to seismic hazards from crustal earthquakes, earthquakes within the subducting slab, and great interface earthquakes.

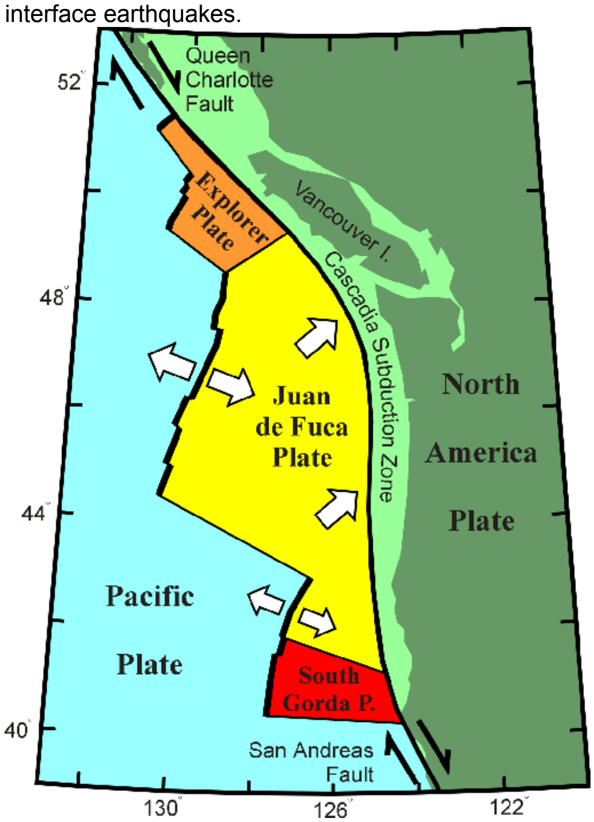


Figure 2. Tectonic elements of western Canada (from www.seismo.nrcan.gc.ca).

Moving away from the west coast, the vast majority of Canada lies within a mid-plate tectonic regime. Seismicity is widespread, as seen in Figure 1, but is characterized by different rates in different parts of the country. Some regions, such as the prairies, are nearly aseismic. As shown in Figure 3, there are several areas, notably along the St. Lawrence Valley and in parts of New Brunswick, that are moderately active. The Charlevoix region of Quebec is very active, with three known large earthquakes (M6 to 7) within the period of historic record (Adams et al. 1995).

In eastern Canada, the nearest plate boundary is the mid-Atlantic ridge, more than 1000 km offshore of Canada's east coast. This plate boundary is too distant to cause seismicity in eastern Canada directly, but is nevertheless important: opening at the mid-Atlantic ridge is responsible for high horizontal compressive stresses throughout eastern North America (Adams and Basham 1989). Pre-existing faults in eastern Canada may be re-activated by the stresses that are driven by ridge push in the mid-Atlantic.

Figure 3 superimposes a schematic of the tectonic framework for seismic hazard in eastern Canada on the portrayal of seismicity. Of particular importance are a 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. 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. A variety of other factors, such as weakening of the crust by a meteorite impact in the Charlevoix region about 300 million years ago, and passage of a hotspot under western Quebec may also be important (Basham et al. 1982).

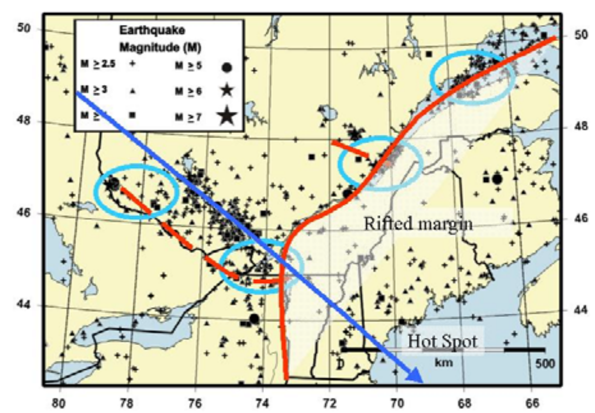


Figure 3. Geological model of eastern Canadian seismicity, according to the rift model of Adams et al. (1999). Historical clusters of seismicity along the St. Lawrence and Ottawa valleys (circled) are related to early rifting of the Atlantic Ocean (lines show former rifted margin). Seismicity in west Quebec may be related to passage of ancient hot spot (arrow).

## 3. AN HISTORICAL OVERVIEW OF SEISMIC HAZARD ANALYSIS IN CANADA

How has seismic hazard been accommodated in engineering design in Canada? The first edition of the National Building Code of Canada (NBCC) in 1941, in which the seismic provisions appeared in an appendix, followed concepts that were introduced in the 1937 U.S. Uniform Building Code (Heidebrecht et al. 1983). The impetus for inclusion of these seismic provisions 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.

In the 1953 edition of the NBCC the earthquake loading requirements were updated and placed in the main text. This also marked the introduction of the first seismic zoning map of Canada, which was qualitative in nature (Hodgson 1956). A major watershed for seismic design philosophy in the NBCC, and the forerunner for its current provisions, 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. These developments were guided by Davenport’s knowledge of the empirical relations and distributions that fit many natural phenomena such as wind gusts and waves (Milne and Davenport 1969). They showed that the general form of these relations was consistent with the Gutenberg-Richter magnitude recurrence relation (Richter 1958) and the observed relationship between acceleration and magnitude. 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 1970, seismic hazard maps have been developed for building code applications based on a probabilistic approach. The maps that appear in the NBCC from 1985 through the present were developed in the early 1980s. After 1970, there was a shift in the method used to calculate the hazard maps. 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 some 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 M7, while Mx for rifted mid-plate regions such as the St. Lawrence Valley would be about M7.5, 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).

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 (PGA) or velocity (PGV), 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). 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) and U.S. National Research Council Panel on Seismic Hazard Analysis (1988). Because of its ability to incorporate both seismicity and geologic information, the Cornell-McGuire method quickly became widely used and popular. Its application to seismic zoning in Canada has been described by Basham et al. (1982, 1985) and Adams et al. (1999).

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 (Atkinson et al. 1982). 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. 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 fact 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?

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 new methodology to 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 many significant 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. Thus the problem has come full circle, with source zones being first considered an advantage, then later viewed as a potential liability.

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) 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 (Halchuck and Adams 1999; see also Figure 5).

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 deaggragating 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 4 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 4 shows that the hazard at Montreal for this probability is dominated by earthquakes of about M6.5, occurring within 50 km of the city.

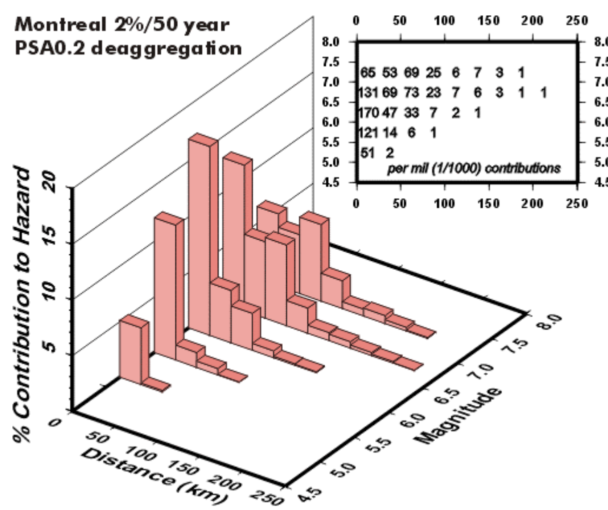


Figure 4. Hazard deaggregation for Montreal, for 2% in 50 year PSA for period 0.2 sec, according to hazard calculations of Adams et al. (1999).

## 4. SOME CURRENT SEISMIC HAZARD ISSUES

### 4.1 Two Common Misconceptions

There are two common misconceptions about probabilisitic seismic hazard analysis. The first misconception arises because of a trend over the last few decades to base seismic zoning maps and standards for critical structures on ground motion values having increasingly low probabilities. For example, the 1970 NBCC earthquake design provisions were based on ground motions with a 100 year return period (0.01

per annum), the 1985 map was based on a 500 year return period (10% in 50 years), and the maps for the next NBCC will be 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 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.

Another misconception is that probabilistic analyses are of suspect reliability due to limited knowledge of the component processes and large uncertainties in their interpretation, and that these uncertainties become particularly pronounced at low probabilities. The important role of uncertainty is a valid issue that is carefully addressed in state-of-the-art seismic hazard analysis. Each of the input components of the problem is indeed subject to considerable uncertainty. It should be understood, however, that uncertainty is inherent, and not specific to probabilistic analysis.

4.2 Recent Advances in Seismic Hazard Analysis

4.2.1 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 and uncertainty in knowledge (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. Uncertainty arises from our incomplete knowledge of the physical mechanisms that control the random phenomena; it can be reduced by collecting additional information.

The seismic hazard maps developed for previous building codes (e.g. Basham et al. 1982) incorporated randomness (e.g. the variability in the ground motion relations), but were known to be sensitive to uncertainty. In recent years, a formal method of handling this uncertainty has been developed (McGuire and Toro 1986; Toro and McGuire 1987), 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 is implemented in the most recent seismic zoning maps for Canada (Adams et al. 1999) and used in site-specific analyses for critical structures in Canada.

4.2.2 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 1970, the NBCC seismic hazard maps presented expected levels of peak ground acceleration (PGA). In 1985, the NBCC maps showed PGA and PGV for the specified probability level. Similarly, early Canadian standards for critical facilities were based on evaluation of PGA and/or PGV. For engineering design, the most useful description of ground motion is a response spectrum (typically PSA, the pseudoacceleration spectrum), which defines the response of a simple 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 (eg. Newmark and Hall 1982) to the site-specific PGA and/or PGV. 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). 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

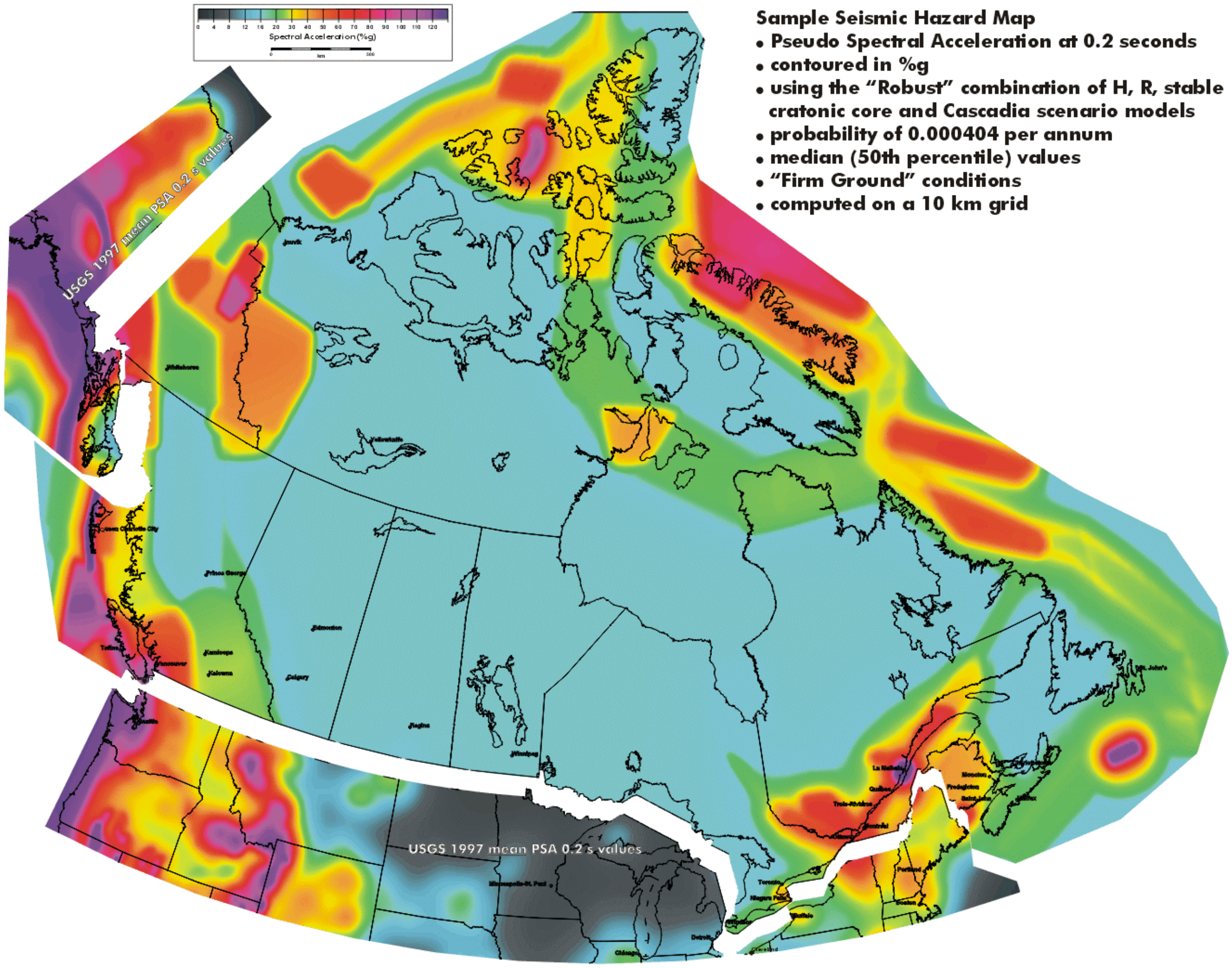


Figure 5. Seismic hazard computed for 2% in 50 year probability across Canada(Adams et al. 1999) and compared to calculations by U.S. Geological Survey in adjacent regions. Colours show PSA for 0.2 second period, where hot colours are largest values (maximum values are about 120%g)

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. This evolution could apply to either the Cornell-McGuire method, or to amplitude recurrence distribution methods. (Note: the primary motivation for the development of standard spectral shapes in the 1960s and 1970s was to overcome the lack of ground-motion relations for response spectra).

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 1982, 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 the latest seismic hazard maps of Canada, a UHS approach is used to overcome previous shortcomings of the scaled-spectrum approach and more accurately describe the site-specific frequency content of the expected ground motions. A similar change has been made in the approach to seismic hazard mapping in the United States (Frankel et al. 1996, 1999; NEHRP 2000).

### 4.2.3 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. For example, the current NBCC is based on motions with a probability of 0.002 per annum (10% in 50 years), while the next edition will move to 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 the country 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 only a little 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. 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 in Canada 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 et al. 1999), ground motions are calculated for an exceedence probability of 2% in 50 years. This is also consistent with recent parallel developments in the United States Frankel et al. 1996; 1999; NEHRP 1997, 2000;).

Finally, there have been significant advancements in our understanding of the physical processes that control seismic hazards in Canada, as described by Adams et al. (1999). Through improved seismographic monitoring with increasingly sophisticated instrumentation, we have a better picture of the distribution of seismicity in Canada, its underlying causes, and the ground motions that are produced. These advances have resulted in new seismic hazard maps for Canada (Adams et al. 1999), which will beincorporated into the 2005 edition of the National Building Code. Figure 5 shows one such map, for response spectral acceleration (PSA, 5% damped, horizontal component, firm ground conditions) at a natural period of 0.2 seconds.

## 5. AN EVALUATION OF HOW FAR WE'VE COME

With all of the advances in knowledge and methodology over the past few decades, one might expect current seismic hazard maps like those of Figure 5 to look very different from the first probabilistic seismic hazard maps of Canada, produced by Milne and Davenport in 1969. It is instructive to examine the extent to which our advances have influenced seismic zoning. Let's compare the most recent seismic zoning map (Adams et al. 1999, as shown on Figure 5) to Milne and Davenport's map, prepared 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; Halchuck and Adams 1999). As discussed earlier, it is based on the Cornell-McGuire method, using spectral ordinates, with 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 6 superimposes the latest seismic hazard results 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 countered by other factors that are used to calculate the seismic loads. With each new seismic map development, there has been a 'calibration' of the code provisions back to the 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 (Heidebrecht et al. 1983). 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 affect 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 6, 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 (the 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.

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 historical seismicity (Figure 3). Seismicity is concentrated in diffuse but reasonably well defined

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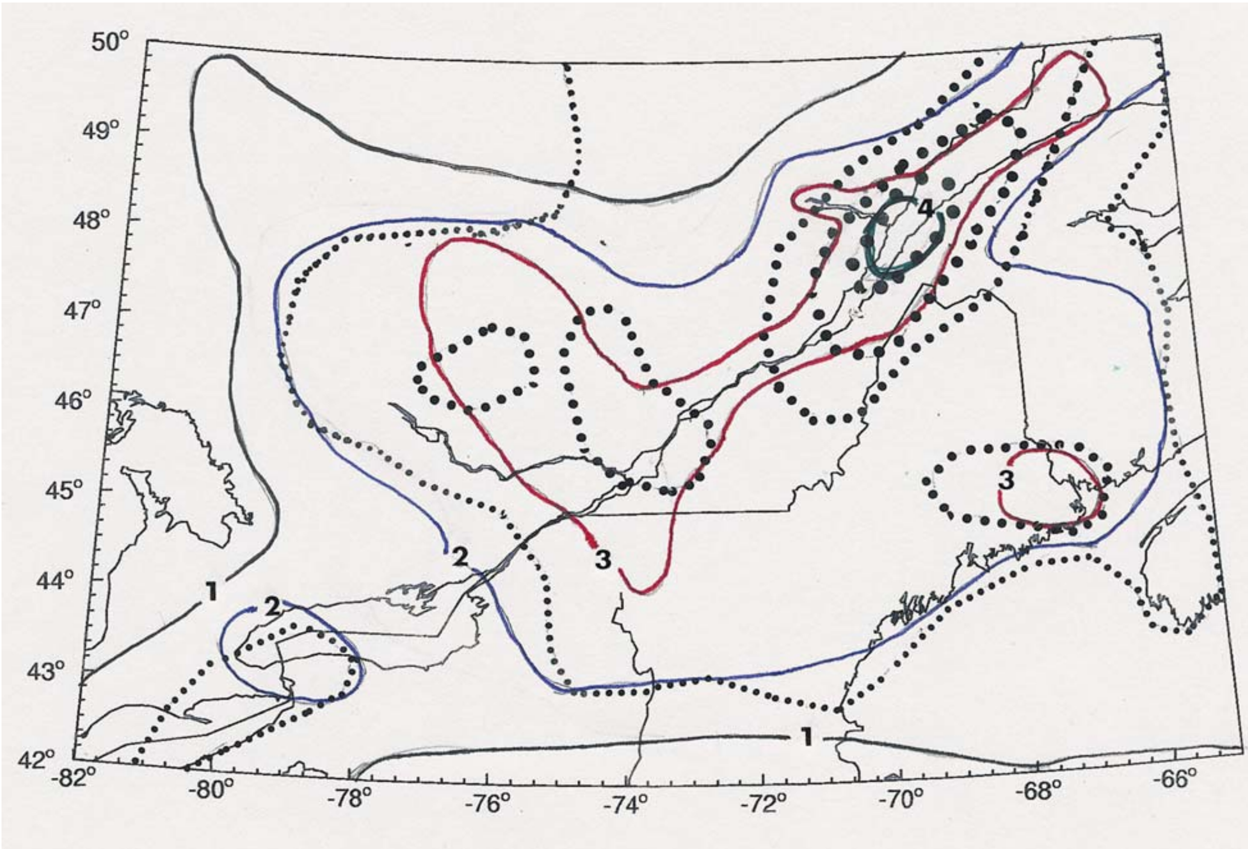



Figure 6. Comparison of seismic amplitude contours defined by Milne and Davenport (1969, dotted lines) to those defined by Adams et al. (1999, solid lines), and proposed for inclusion in the next NBCC. Contours have been renumbered 1 to 4 (solid lines correspond to 0.2 sec spectral acceleration of 16% g, 32% g, 60% g and 120% g, respectively, for a return period of 2500 years).

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). 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 understanding of where and why earthquakes occur, and improved our characterization of the resulting ground motions and their probabilities.

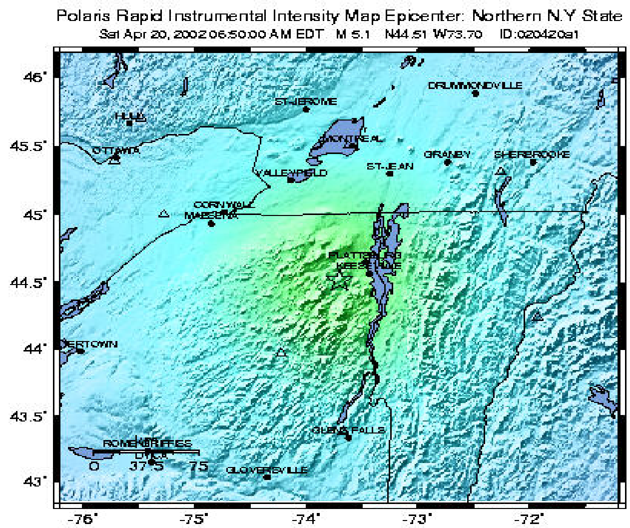
## 6. SOME COMMENTS ON NEW DEVELOPMENTS

Over the last 5 to 10 years, seismological horizons have expanded significantly with the remarkable increase in recorded ground-motion data from earthquakes in all parts of North America. The ground-motion database has improved due to a combination of developments in seismometry and increased deployments of instruments. In well-instrumented regions like California there are now thousands of available strong-motion recordings. From these, we can develop a much better understanding 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). Even in Canada, 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.

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. An exciting geophysics project in Canada that explores this frontier is POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity). POLARIS is multi-institutional infrastructure, with funding from the Canada Foundation for Innovation, provinces and industry, that comprises mobile geophysical observatories that transmit continuous real-time data to research centres using a satellite-telemetry communications system. The major components of POLARIS, when fully installed in 2004, will be 90 seismograph and 30 magnetotelluric (MT) mobile field systems, complementary data-acquisition and satellite-communications equipment, and satellite downlink facilities. The seismograph network comprises three subarrays of 30 3-component broadband seismographs, sampling at 40 to 100 samples/second, to be deployed in Ontario, southern British Columbia, and the Northwest Territories. The POLARIS network complements and works in tandem with the Canadian National Seismographic Network. Researchers from around the world can visit www.seismo.nrcan.gc.ca for CNSN locations and waveform downloads, or www.polarisnet.ca for POLARIS data. These data are available in near-real-time, facilitating the development of real-time seismic 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). In the 1999 Truckee, California earthquake of M7, rapid-warning information was available to stop trains before they traveled into areas where track damage was likely to have occurred. 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.

Seismologists in Ontario are currently developing the tools required to rapidly calculate maps of ground shaking in southern Ontario, including the calculation of response spectra at specific locations. A system to alert provincial, municipal and industrial subscribers (such as Ontario Power Generation) of an event and rapidly disseminate the ground-motion information is also under development. Such information is highly useful to industrial operators of critical facilities, even in the case of small-to-moderate events that produce no damage. For these small events, quick access to information can be used to demonstrate that the motions that occurred were well below the design levels for the facilities, thus meeting regulatory or safety requirements while avoiding unnecessary slow-downs or inspections.




| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

Figure 7. Example shakemap for M5 Au Sable Forks, NY earthquake of 2002, showing instrumentally-determined intensities based on measured PGV. Actual measured intensities were slightly larger in the epicentral region.

An example shakemap for the April 2002 M5 earthquake in upstate New York is shown in Figure 7. This is not an ideal illustration for the technology, as the New York event occurred outside of the Ontario network, before most of the current stations had been installed. Nevertheless it shows the type of information that can be produced within a few minutes of an earthquake with real-time communications and analysis technology. The map is shaded according to the estimated intensity of the motion, based on measurements of peak ground velocity. The estimated intensities from the instrumental data are in the range of IV to V over a broad region, corresponding to strong shaking just below the damage threshold. This agrees in general with actual intensities (available from community intensity surveys that took place in the days following the event), although there were pockets of higher intensity (VI) in the epicentral region. The failure of the current maps to determine pockets of high damage is not surprising, as the maps do not as yet contain information on local soil conditions that is needed to refine the estimates, and are based on few stations. As this technology is developed over the next few years, maps such as this one will become more accurate, more useful, and commonplace. Real-time hazard analysis offers much promise as a means by which the consequences of future earthquakes might be not just estimated, but actually changed.

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