SEISMIC HAZARD MAPPING OF NEW ENGLAND

A project

submitted by:

RICHARD J. DRISCOLL, E.I.T.

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Advisor: Professor Laurie G. Baise

ABSTRACT

The National Seismic Hazard maps developed by the United States Geological Survey provide fundamental parameters for determining the seismic loadings in the design and analysis of structures. In this study, a probabilistic seismic hazard analysis was performed for New England and surrounding areas, following the Central and Eastern United States (CEUS) procedures used for developing the national maps as described by Frankel and others (2002). To evaluate the applicability of the procedure to New England and its sensitivity to changes in modeling assumptions, two changes were made to input data based on the assumption that a higher quality earthquake catalog exists for New England than the rest of the CEUS. The large magnitude event catalog was extended to include the period from 1638 to 1700 following the work of Ebel (1996). Adjustments to account for catalog incompleteness made by Mueller, et al (1997) were removed. Geographic Information Systems was used to process input and output data and calculations were performed by a Visual Basic application running in Microsoft Excel. The New England maps developed in this study were compared with USGS maps from 1995, 1996 and 2002. It was found that the mapping procedure is relatively insensitive to changes in modeling assumptions, indicating that it is applicable to New England and can form the basis for a customized seismic hazard analysis.

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I. INTRODUCTION

Seismic loads usually must be considered when developing a load envelope for the design or analysis of structures, and may be the controlling lateral load. There are a variety of methods used to determine the seismic forces that a structure may have to withstand, however, for many simple, non-critical and non-monumental bridges and buildings, design codes provide simplified procedures that engineers can use with a very basic understanding of the underlying theory. Central to code-based seismic design are seismic hazard maps, which provide a ground motion parameter, usually an acceleration value, which is applied as a lateral force to some part of the structure. In depth understanding of the concepts behind the development of the maps is only necessary when designing structures with exceptionally long lives or very high consequences of failure.

The first national seismic hazard maps were developed by the United States Geological Survey (USGS) in 1976 and provided peak ground acceleration with a probability of exceedance of 10% in 50 years, which corresponds to a 474 year return period. Derivative forms of this map were found in the 1985 and 1988 editions of the *Recommended Provisions for the Development of Seismic Regulations for New Buildings* of the National Earthquake Hazard Reduction Program (NEHRP). The NEHRP *Provisions* are the basis for the seismic design provisions for most model building codes. Later USGS efforts included maps of peak acceleration and velocity and maps of ordinates that could be used to develop design response spectra, which could be used to determine the effect of ground motions with the same period as a structure. These were incorporated in subsequent editions of the *Provisions*, usually a few years after their development. (Leyendecker, et al, 1995)

Procedures used in developing the maps evolved between each edition, with additions and refinements made after a consensus review process. The most recent version of the maps is described by Frankel, et al (2002) and is based on work by Frankel (1995) and Frankel, et al (1996). The contiguous 48 states are split roughly at the Rocky Mountains and different procedures are used on each side of the divide. Multiple models incorporating major known faults, spatially smoothed historic seismicity and background seismicity zones are combined with multiple ground motion estimates to account for uncertainties in modeling. The 2002 maps can be expected to become the foundation of seismic design for the next several years.

Depending on the applicable code, seismic design is required in most, if not all of the United States, including New England where earthquakes are not in the forefront of the public's consciousness. Many people in this area have never felt an earthquake. Yet, the northeastern United States and contiguous parts of Canada have a long history of minor and moderate earthquakes, which have been documented since before the arrival of Europeans in the New World. Far from the continental plate boundaries, which are responsible for much of the world's seismic activity, northeast earthquakes do not occur at easily identifiable sources, and are therefore more difficult to characterize and predict. The last tectonic activity near the Northeast was the collision and rifting that built the Appalachians, yet the area is still seismically active. Seismicity is particularly active along the coast of Maine, the Merrimack valley and Lakes Region of central New Hampshire, eastern

Massachusetts, the Connecticut River Valley in Connecticut, the New York metropolitan area, the Champlain valley and St. Laurence Valley. (Ebel & Kafka, 1991)

The procedures used to calculate seismic hazard in New England are the same as for all states east of the Rockies, an area referred to as Central and Eastern Untied States (CEUS). Assumptions made to model earthquakes for the whole CEUS, however, may not be most appropriate for modeling New England. It may be questionable, whether seismic hazard should be determined for an area like New England, where earthquakes are somewhat frequent and poorly understood, and where the consequences of damaging ground motions are great, using the same procedures as where considerably lower hazard exists. For example, the earthquake recurrence model used by Frankel (1995) for the CEUS hazard calculations is a form of a model developed using data from California, where earthquakes are better understood and usually occur at identifiable sources (Kramer, 1996). The model may not adequately describe New England events.

New England has one of the longest and most complete historic earthquake catalogs in North America due to the length of time the area has been settled, and more recently, due to extensive instrumentation. Intensity reports are available for moderate to large events, events larger than Lg magnitude of 5.0 (m_{bLg}, a magnitude scale used to describe interplate earthquakes), from the early 17th Century. By analyzing the intensities of an unusually large earthquake on 11 June 1638 felt in the St. Lawrence River Valley and Massachusetts Bay, Ebel (1996) demonstrated that a m_{bLg} 6.5 to 7.0 earthquake in the southern portion of the seismically active region of central New Hampshire could have caused the effects experienced in both locations, including the aftershocks of magnitude 4.0 felt in Boston. Another larger earthquake in February 1663 near Charlevoix, Quebec resulted in major landslides and liquefaction. Large enough to be felt by all in Quincy, MA (Intensity V-VI), the magnitude was estimated to be m_{bLg} 7.0±0.5. A 16 October 1665 earthquake of m_{bLg} 5.0 near Quebec City was felt in Roxbury, MA. Two and one-half year later on 13 April 1668 another Canadian event was felt in the Boston area. Damage suggested an epicenter near Cape Tourmente, Quebec and a magnitude much larger than 5.0 (Ebel 1996).

An extensive catalog allows recurrence models to avoid bias from using an unrepresentative period of time. The current National Seismic Hazard Maps developed by the United States Geological Survey (USGS) does not, however, consider any events before 1700 such as those located by Ebel (1996). While the rate of moderate and large events during the 17th Century is similar to that during the 20th Century, the rate of large events was elevated. In the source area considered in this study, four m_{bLg} 6.0 and greater events occurred between 1700 and 2003. Two more, the 1638 New Hampshire event and the 1663 Charlevoix event occurred in the prior century. This would appear to be a serious oversight in developing design ground motions for New England and adjacent regions. If the recurrence rate of large earthquakes is underestimated in developing the maps, the ground motions experienced by a structure in New England during its design life may be larger than expected.

Another issue related to catalog quality is the use of factors to adjust pre-instrumentation seismicity rates to match those of the present. Prior to instrumentation, seismologists used human observations to characterize earthquakes. Magnitudes and location of historical earthquakes can be estimated from these felt intensity reports. The problem with using human observations to develop an earthquake catalog is earthquakes that are small or occur in unpopulated areas cannot be felt. The omissions result in an earthquake catalog that is more incomplete for earlier historical events. The recent versions of the maps used a weighting system to adjust seismicity rates to equal the period after instrumentation to account for incompleteness of catalogs (Mueller, et al 1997). This is problematic because it assumes that current and past recurrence rates should be equal. By giving higher weights to known events, it is effectively assumed that earthquakes that were not observed occurred in the same location as those that were observed. A more complete catalog would prevent having to make this assumption. The current maps group New England with the rest of the eastern seaboard in developing factors to adjust seismicity rates. The use of seismic rate adjustment factors (SRAFs) developed for such a large area may not be representative for New England, where a more extensive catalog exists due to length of time for which the Northeast United States and Southeast Canada have been settled.

The purpose of this study was to evaluate the applicability of the national seismic hazard maps produced by the USGS and incorporated in the NEHRP *Provisions* for use in New England. Hazard maps were made for peak ground acceleration with a probability of exceedance of 10% in 50 years following the procedures referenced in Frankel, et al (2002). Two assumptions regarding the New England catalog were tested: the effect of including large events of the 17th Century and the effect of changing the seismic rate adjustment factors. To test the assumptions an extended catalog was created including the years 1638 to 1700 and used to develop maps. SRAFs were changed from those used in the USGS maps to 1.0, effectively assuming that the historic catalog was complete for New England. Four maps were produced: one closely followed Frankel, et al, one used the same procedure with the extended catalog, one used the Frankel, et al procedure, but set all SRAFs to 1.0, and one performed both experiments simultaneously.

Although assumptions used in preparing national seismic hazard maps may not be completely applicable to a particular area, like New England, it is possible that the effect of the assumptions becomes negligible when multiple recurrence and ground motion attenuation models are combined. In analyzing the effect of modeling assumptions, it is necessary to understand the sensitivity of the process as a whole. By comparing the maps created for this study with each other as well as with current and past editions of the USGS, the effect of several smaller modeling assumptions could be analyzed. The similarity of the maps when various parameters are altered will demonstrate the sensitivity of the procedures. It will also indicate whether this procedure can be used as a basis for a customized seismic hazard analysis.

The New England Seismic hazard maps developed in this study will be developed using readily available published sources, however, the complete procedure is not in a single publication in such a form that it can be followed step by step. Therefore additional assumptions and judgments will be required. To facilitate this, theories explaining New England earthquakes will be reviewed, as will be the fundamentals of seismic hazard analysis behind site specific and code-based seismic design. With this background information, the seismic hazard calculation will be performed paralleling the work of Frankel, and others (2002). The procedure and any changes or assumptions made will be presented simultaneously to facilitate analysis. The completed maps will be compared and contrasted with each other and with the national maps from 2002 and earlier. The effect of extending the catalog, adjusting seismicity rates and other assumptions will be discussed in terms of the sensitivity to these variables. Finally, some recommendations will be made regarding the application of the maps to New England, and in general.

II. BACKGROUND

The national seismic hazard maps are fundamental to code based seismic design. Many structural design standards require the consideration of seismic loads. The ANSI/ASCE 7-*Minimum Design Loads for Buildings and Other Structures* is a national standard that includes seismic design procedures. Seismic provisions are provided by regional model building codes such as the Uniform Building Code by the International Conference of Building Officials, used in the western United States, the Building Official and Code Administrator's (BOCA) National Building Code (NBC) used in the northeast, and the Southern Building Code of the Southern Building Code Congress International used in the south. The seismic provisions in these model codes are based on the National Earthquake Hazard Reduction Program (NEHRP) *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. (Leyendecker, et al, 1995) The International Code Council, an organization of the three building code agencies, produced the International Building Code (IBC) to replace its members' model codes, and also used the NEHRP *Provisions* (BOCA, 2001). The Association of American State Highway and Transportation Officials (AASHTO) also include seismic provisions in their design standards. Some states, including Massachusetts, have their own building codes. Massachusetts adopted seismic provisions in 1980 (Alsup and Franz, 1989).

The NEHRP model code imposes a base shear load to a structure that is proportional to its weight. The proportionality constant is a function of the fundamental period of the structure, the response modification factor, which depends on the type of construction, and constants that account for ground motion and soil type. The ground motions used by NEHRP are the effective peak acceleration (EPA) and effective peak velocity (EPV), which are proportional to the average spectral acceleration for low period (0.1 to 0.5 sec) and the average spectral velocity for longer period (1.0 sec.), respectively. EPA is presented as a fraction or percent of gravitational acceleration. The ground motion constants used to calculate base shear are the product of the EPA and EPV and their respective site soil condition factors. EPA and EPV values are obtained from seismic hazard maps of ground motions with probabilities of exceedance in 50 years of 10%. (Kramer, 1996) The maps used in the NEHRP Provisions are among those developed by the USGS using the procedures discussed by this study (Frankel, 1995).

Highway Bridges are designed using the AASHTO Bridge Design Specifications. AASHTO's seismic provisions provide charts of horizontal acceleration coefficients, expressed as a percent of gravitational acceleration, with 10% probabilities of exceedance in 50 years. The ground acceleration map in the 1994 bridge specification was adopted from the 1988 NEHRP model code (AASHTO, 1994). The acceleration coefficient is selected from the NEHRP seismic hazard maps and determines which seismic performance zone is selected. The importance of the bridge and the response modification factors must also be selected. During an earthquake, each segment of the bridge superstructure is assumed to maintain its integrity and the force or displacement at the supports is determined. For single span bridges, regardless of seismic zone, and all bridges in the lowest seismic zone, the connection force is the product of the acceleration coefficient and the tributary area dead load. More rigorous analysis is required for bridges of higher seismic risk, greater importance and irregular geometry. For these bridges, an elastic seismic response coefficient, which is a function of the site conditions, acceleration coefficient and fundamental frequency, is multiplied by the dead load to obtain an equivalent lateral load to be applied to the connection. For the most at risk bridges, time histories and response spectra are required. (Barker and Pucket, 1997)

It is often necessary to perform site-specific analyses when site conditions fail to conform to the applicable design code or, when a variance to the code is desired. Sometimes, the site-specific analysis consists of determining the site response to the ground motions specified by code, however a complete seismic hazard analysis can be performed and customized for the specific requirements of a given site or project. Regardless, the determination of seismic loads at a site directly from seismological data and models, without the use of building codes is called a seismic hazard analysis. It will be shown that the seismic hazard maps found in design codes are the result of performing a large number of very generalized seismic hazard analyses for a very large number of points in a region.

A Seismic Hazard Analysis is a quantitative estimation of strong ground motion at a particular site, which can be used to design structures to withstand the estimated motion without excessive structural damage or collapse. For many structures, it is the peak horizontal acceleration (PHA) or peak ground acceleration (PGA) that is of interest in earthquake resistant design. Ground motions can be estimated deterministically, where they are predicted for an expected maximum magnitude earthquake, or they can be found probabilistically, which accounts for uncertainty in source location, earthquake magnitude and rate of occurrence. In either case, all credible earthquake sources are considered and ground motions predicted at the site for a set of events at that source.

Deterministic analyses involve postulating a critical event size, location and effect on a site. To perform this type of analysis all significant earthquake sources are characterized according to their potential and distance from the site. The controlling earthquake for the site is defined in terms of potential ground motion and the ground motions used for design. A deterministic analysis is appropriate when the worst case scenario should be used for the design of long term or failure critical structures, such as large dams and nuclear power stations, but requires a great deal of subjectivity and expertise. (Kramer, 1996)

A more rational and typically less conservative approach is the probabilistic seismic hazard analysis (PSHA), where uncertainties can be identified, quantified and combined more completely. This process is used in developing the National Seismic Hazard Maps for code-based design. The general procedure is similar to deterministic analysis. Earthquake sources are identified and characterized according to spatial and temporal models. Ground motions for each possible earthquake at each possible source are calculated along with their respective probabilities. Combining the uncertainties in source, spatial and temporal distribution and ground motion yields the probability of exceedance for the ground motion calculated for a particular period of time. (Kramer, 1996)

The probability of exceedance for a specific ground motion, u, is the sum of the exceedance probabilities for the ground motion for every possible magnitude event at all locations of each source. For continuous functions, it is therefore the integral over distance and magnitude of the product of the probability density functions for magnitude, $f_M(m)$ and distance $f_R(r)$ and the probability of exceedance for the ground motion given a magnitude and source to site distance, $P[U > u \mid m, r]$. For a given source the total probability of exceedance is as shown.

$$P[U > u] = \iint P[U > u \mid m, r] \; f_M(m) \; f_R(r) \; dm \; dr$$

This integral is evaluated for each source and the results summed. Typically, the integration is too difficult to solve analytically, requiring the discretization of the probability density functions. The continuous integral is broken into a step function where the discrete value at a point estimates the value of the functions over a range of magnitudes and distances.

It is often useful to express probability of exceedance as an annual rate of exceedance. Including all earthquake sources and the rates of exceedance for a given magnitude on each source, ν_{ij}, the annual rate of exceedance for the ground motion, u, λ_u is:

$$\lambda_u = \sum_{i=1}^{N_S} \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} \nu_{ij} \; P[U > u \mid m_j, r_k] \; f_M(m_j) \; f_R(r_k) \; \Delta m \, \Delta r$$

where $N_{S,}$ N_M and N_R are the number of sources, magnitude and distance ranges or bins identified by the index variables i, j and k The above formulation is really an estimate of probability, and its accuracy increases with the number of bin. The uncertainty introduced by discretizing is low, however, compared to the uncertainty in the estimation of probability functions for the ground motion, magnitude and source. The additional uncertainty in the probability estimate from using a discretized form is not typically considered, and will not be explicitly treated in this study. (Kramer, 1996)

The geometric models used to represent earthquakes sources depend on the type of process assumed to be causing the earthquakes. Events associated with volcanoes can be thought of as one-dimensional point sources, while known faults can be modeled as two-dimensional sources. Areas where a causative mechanism is unknown can be represented as three-dimensional sources. Neglecting the depth of the source can simplify the spatial model. Typically earthquakes are assumed to occur with equal likelihood anywhere in the source zone. The uncertainty in event location is described in terms of a probability density function for source-to-site distance, which may be evaluated analytically in the case of a linear source or using numerical or graphical approximation for more complicated geometries. (Kramer, 1996)

A recurrence law describes the temporal distribution of earthquake magnitudes for a given source and can be used predicatively, assuming that past and present seismicity is indicative of future events. A common form of recurrence law was developed by Gutenberg and Richter and defines the mean annual rate of exceedance, λ_m, as the number of exceedance of a specified magnitude during some period of time, or the inverse of the return period of earthquakes exceeding that magnitude. They observed that a plot of the magnitude versus the logarithm of the annual rate of exceedance for Southern California earthquakes formed a linear trend:

$$\text{Log } \lambda_m = a - bm$$

The intercept, a, is the power of 10 equal to the total mean number of events per year and the slope, b, describes the relationship between event size, m, and return period. (Kramer, 1996)

A Gutenberg-Richter recurrence law can be developed for any source zone with an adequate historic catalog by performing a linear regression analysis and solving for the a and b values. The catalog must be complete for the period of time considered, must use a consistent magnitude scale and must be purged of foreshocks and aftershocks. In less active areas, such as New England, catalogs must rely on instrumental catalogs as well as historical records to contain enough data to adequately describe larger events. The problems with such a catalog is that historic catalogs are usually only complete for large events that can be observed without instruments over large areas causing the rate of smaller events to increase closer to the present. Historic catalogs also often lack instrumental magnitude reading and may not use the desired scale. In either case conversion is required increasing uncertainty associated with the model. (Kramer, 1996)

Two examples of Gutenberg-Richter recurrence laws were used by Ebel & Kafka (1991) to define seismic zones in the Northeast United States. These follow the above form except that they are normalized by area. The first is a cumulative recurrence relationship for the northeastern United States using data between 1975 and 1986:

$$\text{Log } N(/\text{yr}/10{,}000 \text{ km}^2) = 1.72(\pm 0.06) - 0.93(\pm 0.02)M$$

This predicts the return period of magnitude 5, 6, and 7 earthquakes to be 14, 122, and 1039 years respectively for the Northeast. This relationship was compared to actual seismicity. Between 1900 and 1991 there were seven magnitude 5.0 or larger events, including the two 1940 Ossipee earthquakes, while the recurrence relationship predicted six. One magnitude 6.0 or greater event was known since 1700; two were predicted. (This work predates Ebel, 1996) Including the 1638 New Hampshire earthquake makes the recorded and predicted seismicity nearly equal.

The second recurrence relationship is for New England only, based on data from October 1975 through November 1982, and is of similar form, but does not fit actual catalog data as well:

$$\text{Log } N(/\text{yr}/10{,}000 \text{ km}^2) = 1.55(\pm 0.09) - 0.84(\pm 0.03)M$$

(Ebel & Kafka, 1991)

A Gutenberg-Richter recurrence law assumes that historic seismicity is indicative of future activity. It may be equally valid to hypothesize that routine minor earthquakes may be aftershocks of past large events. Called the paleoseismicity model, by Ebel, et al (2000), this implies that areas of high seismicity are of lower risk from large earthquakes than those of lower seismicity. The temporal decay of aftershocks can be described by Omori's Law, with which the time since an event can be found, given the activity rate, aftershock and main event magnitude and b value from the Gutenberg-Richter recurrence relationship.

$$\text{Log } \lambda_m(t,m) = a + b(M_m - m) - p \text{ Log } (t + 0.05)$$

In this form, the rate of exceedance of the magnitude m is a function of the time, t since a main shock of magnitude M_m, where p is the Omori's law decay exponent and a is related to the rate of exceedance for m = M_m at time = 0.95. This form of recurrence law can be rearranged to find the time since an event of a given size for a source zone. (Ebel, et al, 2000)

Ebel, et al, (2000) demonstrated that this model applies to interplate earthquakes by using it to describe the seismicity of New Madrid and Charleston, SC areas as aftershock sequences of the large earthquakes experienced there. Ebel also found that several clusters of increased seismicity in New England are consistent with the Paleoseismicity model. The current seismicity of the Merrimack Valley of New Hampshire suggested an earthquake of magnitude 6.9 to 7.5 would have occurred within 386 years. Therefore, the modern seismicity in this area is consistent with aftershock activity of the 1638 earthquake believed by Ebel (1996) to have occurred in central New Hampshire. A similar sized earthquake within 689 years in the Lakes Region of New Hampshire would explain the current seismicity there. Assuming that areas of higher seismicity are aftershock source zones showed the possibility that large earthquakes occurred near the New Hampshire/Maine/Quebec border region and the Dover/Foxcroft, ME area within the last several hundred years. (Ebel, et al, 2000)

If current events represent aftershocks of past large events, the seismic hazard analysis would appear to involve predicting the effects of regular aftershocks of declining magnitude. However, the reality may be more complicated. The seismicity of Cape Ann does not account for the 1755 earthquake, demonstrating that this model may not be applicable everywhere. In the Charlevoix region of Quebec, events are more frequent than would be predicted if the current seismicity was assumed to be aftershocks from a 1925 earthquake. Earthquakes in the region may, however, be explained considering large events in 1870, 1860, 1791 and 1663. The current activity may be a result of aftershocks from all of the large events in this area. (Ebel, et al, 2000)

The characteristic event model draws from the observation in paleoseismic studies that points on some faults displace by approximately the same length during each earthquake. If the recurring displacement corresponds to a repeated length of fault rupture, then the fault produces earthquakes of similar magnitude called characteristic events. This phenomenon is not well understood, but may be the result of some geologic constraint on the fault. The recurrence law for characteristic events is non-linear and may take the form of a modified Gutenberg-Richter model. (Kramer, 1996) Characteristic events are often large and some of the largest earthquakes in the CEUS, including New Madrid and Charleston, SC have been hypothesized to be characteristic events (Frankel, et al, 1996).

The remaining term in the exceedance rate calculation is based on predictive relationships called attenuation relations used to estimate ground motions as a function of the seismic parameters that most influence the ground motions felt at a given site. Peak ground motions are related to the amount of energy in seismic waves at the source, which is governed by the amount of energy released during the event and the decrease in energy as seismic waves radiate from a source and loose energy to the media through which they travel. Therefore, event magnitude and site-to-source distance are the most important parameters. A regression analysis of ground motion data sets with consistent magnitude and distance measures is used to develop attenuation relations. Common forms of attenuation relations convert the ground motion to its natural logarithm for the regression analysis and account for radiation and damping with distance as well as the increase of amplitude with increased magnitude. The mean ground motion is assumed to have a lognormal distribution and if the standard deviation is known, the probability of exceedance can be calculated conveniently. (Kramer 1996)

The lack of a sufficient earthquake database in Eastern North America (ENA) requires alternative methods to be used to develop ground motion relations. While there is sufficient data in Western North America to develop attenuation relations empirically, ENA relations require a theoretical underpinning. One common approach is referred to as the stochastic method, and uses theoretical models to represent the dissipation and propagation of the energy released by an earthquake and uses random process theory to develop ground motions that fit the model. The ground motion is modeled as band limited, finite duration, and random, Gaussian white noise, modified to reflect the dominance of high frequency Lg waves in ENA waveforms. A constant source stress scaling parameter, or stress drop is assumed. A time series is generated from a random series of waveforms multiplied by an amplitude spectrum. This is repeated with different randomization seed values until the time series spectral shape coincides with the wave propagation model. A regression is then performed on this data to develop an attenuation relation. (Boore & Atkinson, 1987)

The recurrence laws describe seismic hazard in terms of the rate of exceedance of a ground motion parameter estimated from an attenuation relation, but often probability of exceedance is more useful. To describe the probability of an event occurring within a specified period of time, temporal uncertainty must be considered. Seismicity records typically do not suggest that earthquakes follow any temporal pattern, that is, they occur randomly. Recurrence is therefore a random variable that can be described with a simple probabilistic model. The most common model used to describe earthquake recurrence is a Poisson process, which involves a random variable of the number of occurrences of a particular event during a specified period of time. The number of occurrences in a time interval is independent of what has occurred in another time interval. There is no system memory of time, size or location of prior events. The probability of occurrence is proportional to the length of the time interval and the chance of two occurrences in a short period of time is negligible. (Kramer, 1996)

The probability of the random variable representing the number of occurrences, N, is described as:

$$P[\, N = n] = \frac{\mu^n e^{-\mu}}{n!}$$

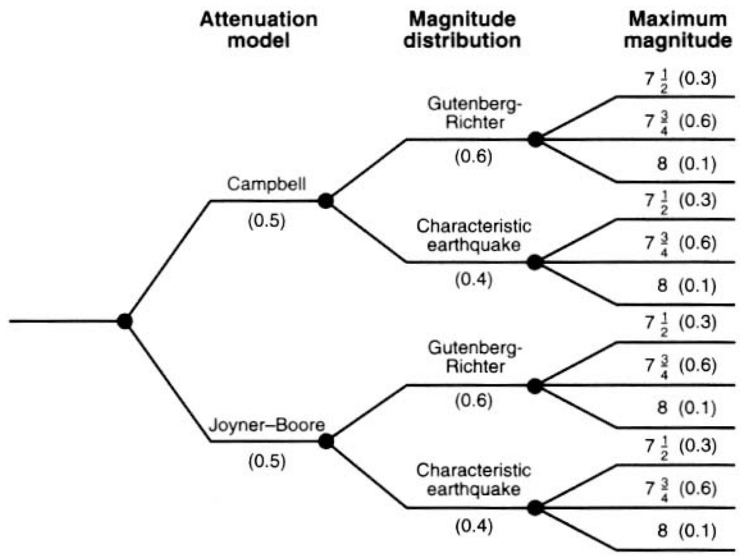
The average number of exceedances in a time interval μ can be replaced with the average rate of exceedance from the recurrence law and the time interval. It can then be shown that the probability that the number of events exceeding some magnitude on a given source is described as follows: (Kramer, 1996)

$$P[\, N \geq n] = 1 - e^{-\lambda m t}$$

This statement can be used to convert an annual rate of exceedance to a probability of exceedance within a certain time period. Alternately, an exceedance rate can be calculated for desired probabilistic criteria. A ground motion can then be selected that occurs with the same rate of exceedance. This logic is behind the development of Seismic Hazard maps.

In lieu of or combined with the mathematical exceedance probability calculation, seismic hazard can be calculated probabilistically using an alternative formulation, particularly when probability density functions are unknown. This method uses logic trees, which consist of a series of elements or branches representing alternative models connected at nodes. Each node represents a step in the analysis where different models are specified. Modeling uncertainty is considered by weighting alternative models at each node proportional to their likelihood such that the sum of the weight at each node is unity. A seismic hazard analysis is performed for each combination of branches and the result weighted by the product of the weights at each node. Figure II-1 shows a simplified logic tree that might be used for a PSHA at a WNA site. For one source, three event magnitudes are considered along with their relative likelihoods. Two recurrence models and two attenuation relations are used. The total result is the sum of the weighted branches. (Kramer, 1996) A logic tree is useful in considering alternate analytical models of known or assumed likelihood and can be combined with the mathematical calculation by using the mathematical form to calculate the value of each combination of elements. A logic tree of this type will be used to describe the procedure for the National Seismic Hazard maps.

Figure II-1. Simple PSHA Logic Tree (Kramer, 1996).



With no nearby tectonic plate boundaries, seismic activity in New England appears to violate the plate tectonic model, which explains earthquakes in terms of fault activity near plate boundaries. The processes that cause earthquakes have been found to be more complicated in plate interiors than at plate boundaries. Identifying a mechanism for interplate earthquakes, like those in New England, is elusive, because unlike earthquakes near plate boundaries, there is not necessarily a correlation between geologically mapped faults and earthquakes epicenters. In the mid-1970s geologist and geophysicists began to focus on finding the cause of earthquakes in New England. (Kafka, 2000)

In 1976 the Boston Edison Company (BECo) conducted a study of New England earthquakes for the Nuclear Regulatory Commission to justify the use of a smaller intensity design event in the design of the Pilgrim II Nuclear Power Station in

Plymouth, MA. The study found that there were four events of concern to the design of a nuclear power station, two earthquakes near Ossipee, NH in 1940, and events of the coast off Cape Ann, MA in 1727 and 1755. The study found that relatively young gabbro plutons of the White Mountain magma series were located near both areas (Simmons, 1976)

The BECo study concluded that the plutons were features with a higher stiffness than the surrounding crust, which disrupted and distorted the stress field. Earthquakes were the result of this stress regime near the gabbrotic plutons. Since plutons could be considered the source of the Ossipee and Cape Ann events, and there were no gabbrotic plutons near Plymouth, lower seismic design standards could be justified in the design of Pilgrim II. (Simmons, 1976) Attributing earthquakes in New England to Plutons was one of many hypotheses explaining New England earthquakes in 1970. Others supposed the existence of a Boston to Ottawa seismic zone, or reactivation of faults in New York and New Jersey (Kafka, 2000). Coastal earthquakes were attributed to subsidence along the Atlantic coast (Barosh, 1989).

Presently, the generally accepted theory regarding earthquakes in New England is that structurally weak geologic features that were formed during ancient tectonic activity exist in the modern crust and are being activated in the current stress field. The crust underlying New England has been subjected to two major geologic events, the collision with the African plate to form the super-continent, Pangea, 250 to 450 million years ago and the rifting of Pangea between 100 and 200 million years ago. (Kafka 2000) Earthquakes occur when stress is released along these pre-existing weak points. Unfortunately, identifying active and potentially active geologic features has not been possible; it is not clear whether causative features are those mapped at the surface or unmapped feature below the surface (Ebel & Kafka, 1991).

Ebel and Kafka (1991) used data from focal mechanism studies in the northeast and adjacent parts of Canada to summarize the modern stress field. They found that the maximum compressive stress was aligned east to west (266°±32°) and that the minimum stress is nearly vertical. Understanding the state of stress may be useful in determining whether conditions favor the activation of a particular fault based on the fault's orientation, however studies of local seismicity fail to show the alignment of epicenters along known faults or other features. (Ebel & Kafka, 1991)

Another possible failure mechanism in a stable crustal region is static fatigue, the failure of brittle materials after some period of time under stress below instantaneous failure. The eastern part of North America is believed to be at a level of compressive stress slightly below its breaking point, suggesting that current seismicity is not indicative of the location of future earthquakes, but represents aftershock sequences of large events of the more distant past. This mechanism is behind what Ebel, et al (2000) called the paleoseismicity model. While smaller or moderate events are to be routinely expected in aftershock zones, the occurrence of large events is not limited to areas of historic seismic activity.

The selection of a recurrence model requires some knowledge of the current stress field and the faulting mechanisms of the source. If New England is a zone of ancient weakness in a critical interplate region at which modern stress is concentrated, current seismicity should be indicative of future events and a typical Gutenberg-Richter recurrence law may be used. If the reverse hypothesis is assumed, and current earthquakes are aftershocks from major events in the Merrimack valley and Lakes Region hundreds of year ago, then small events should be expected from these sources, but, as has occurred in the Charlevoix Quebec area, a future earthquake may be as large, if not larger than those which are suspected to have occurred based on the paleoseismicity model. Since the Paleoseismicity model can only be used to predict aftershocks, a different model would be required to predict the sort of infrequent catastrophic events that awakened the currently active seismic zones. There is currently insufficient data to develop this sort of model.

The national seismic hazard maps developed by the USGS provides important parameters for the code-based design of a variety of structures to resist seismic loads. The maps consist of the results of performing probabilistic seismic hazard analyses on many points. The required components of a probabilistic seismic hazard analysis and their connection have been identified and some of the general choices among models and means of handling uncertainty discussed. The USGS maps use a combination of a logic tree and a mathematical rate of exceedance formulation to estimate the ground motion satisfying specified probabilistic criteria. This study will attempt to recreate the USGS maps and then modify the input information so as to assess the applicability of the procedure to New England and the sensitivity of the calculation. The modeling assumptions of the USGS procedures will be considered in light of the theories explaining New England, as well as the previously discussed catalog information. Next, the procedure used to develop the national seismic hazard maps and deviations from the published procedure and assumptions required to complete the analysis, will be examined in detail and analyzed.

III. PROCEDURE

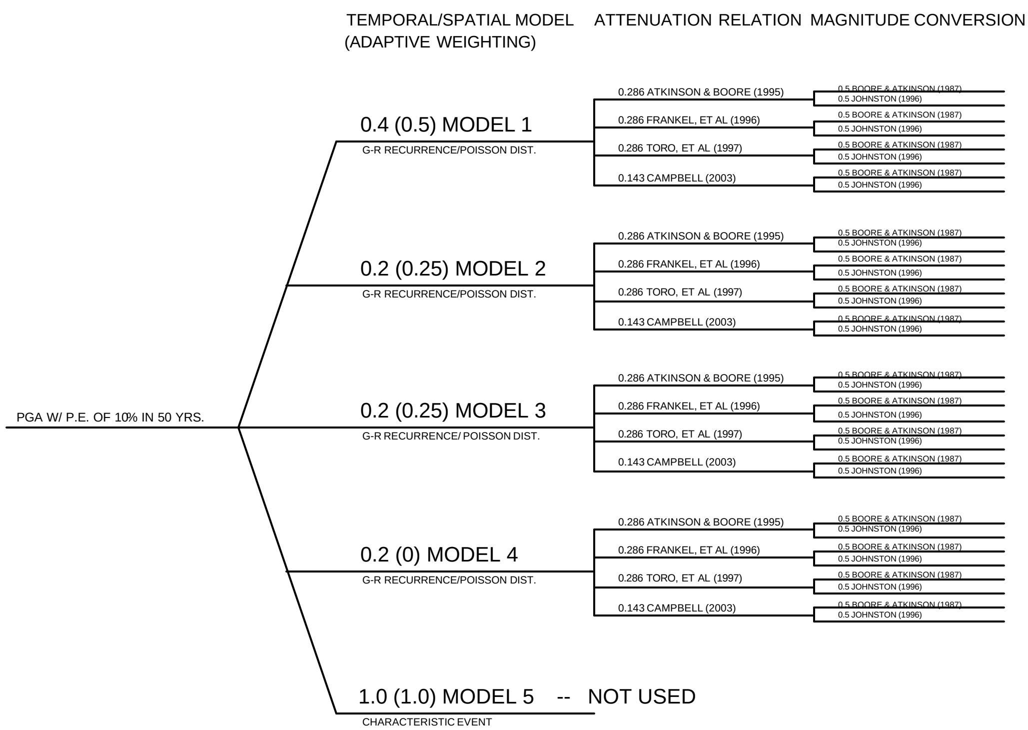
Four maps of peak ground acceleration with a 10% probability of exceedance in 50 years were produced for New England and surrounding areas using three models based on spatially smoothed historic seismicity and one background seismicity model. One map was developed using the USGS models unmodified to validate the process of developing the maps and any small design assumptions. The second map extended the catalog of events for the magnitude 5.0 and greater model to include the 17^{th} Century. A second set of maps using seismic rate adjustment factors of 1.0 was produced to evaluate the effect of using pure historic seismicity versus adjusted seismicity in New England.

The procedure used to develop the seismic hazard maps can be described in terms of the components of a probabilistic seismic hazard analysis as discussed previously. The maps are based on a grid of 0.1° longitude by 0.1° latitude cells. For each grid cell, a PGA value is determined to correspond to the desired rate of exceedance. Figure III-1 shows the logic tree for the seismic hazard calculation for a grid cell after Frankel, et al (2002) as it pertains to this study.

The grid cell value is the weighted average of four models. Model 1 consists of the smoothed rate of m_{bLg} 3.0 and greater events since 1924. Model 2 includes earthquakes greater than m_{bLg} 4.0 while Model 3 is based on m_{bLg} 5.0 and greater events since 1700. It is Model 3 that will be modified to include 17^{th} Century events. Model 4 is the background seismicity zone. A Model 5 exists in the USGS procedure to account for characteristic earthquakes of moment magnitude 7.0 and greater, however it was limited to four areas, New Madrid, Charleston, SC, the Meers fault in

Oklahoma and Cheraw fault in Colorado. None of these areas would be expected to pose a significant risk to New England; therefore this model was ignored. Frankel, et al superimposed Model 5 with full weight on the weighted average of the other four models and therefore its exclusion was not problematic. (Frankel, et al 1996) Frankel, et al (2002) used a finite fault model for magnitudes of 6.0 and greater in calculating gridded seismicity a values, however, this only affected very low probabilities of exceedance (less than 2% in 50years), was not well described and was neglected as well.

Figure III-1. Logic Tree for Seismic Hazard Maps after Frankel, et al (2002)



Four attenuation relations were used; Toro, et al (1997), Frankel et al (1996), Atkinson and Boore (1995) and Campbell (2003). A fifth relation was used for Model 5 on the USGS maps. The attenuation relations used slightly different assumptions, particularly choice of magnitude scale and site conditions. For the attenuation relations requiring moment magnitude (M_w) as an input parameter, conversions by Boore and Atkinson (1987) and Johnston were used to convert m_{bLg} to $M_{w.}$ (Frankel, et al 2002)

Since the analysis was to be performed on a large number of grid cells and the calculation somewhat involved, it became clear that a computer would have to do most of the work. It would also need to process the hundreds of events in the catalog and plot the data at various stages. Therefore a Geographic Information System (GIS) package, ArcMap by ESRI, was selected to process input and output data from the seismic hazard analysis. GIS allows information in databases to be plotted and manipulated spatially and was therefore useful in plotting earthquakes, developing the catalogs for each model, checking processes based on spatial data and plotting results. To perform all calculations, Visual Basic for Applications (VBA) programs were developed and run in Microsoft Excel. VBA is based on BASIC and, although less powerful than other programming languages, it is convenient to learn. By writing programs to be executed in Excel, input and output is simplified. VBA is available in GIS and proper database programs; however, its use in Excel is better documented and represented a more expedient choice. (See Chapra, 2003)

The basic algorithm used in this study for developing the seismic hazard maps is as follows: For each model, the proper events were selected from the earthquake catalog. Using GIS, the number of events falling into each grid cell were counted. The cell counts were spatially smoothed using a VBA subroutine. The seismic hazard calculation program used the smoothed counts for each model to determine the rate of exceedance of a trial PGA value. The trial PGA was adjusted until the rate of exceedance converges upon that corresponding to 10% in 50 years. This process was repeated for all cells in the selected source region and for all models. The PGA values for all four models contributed to a total value, which was plotted as maps by GIS.

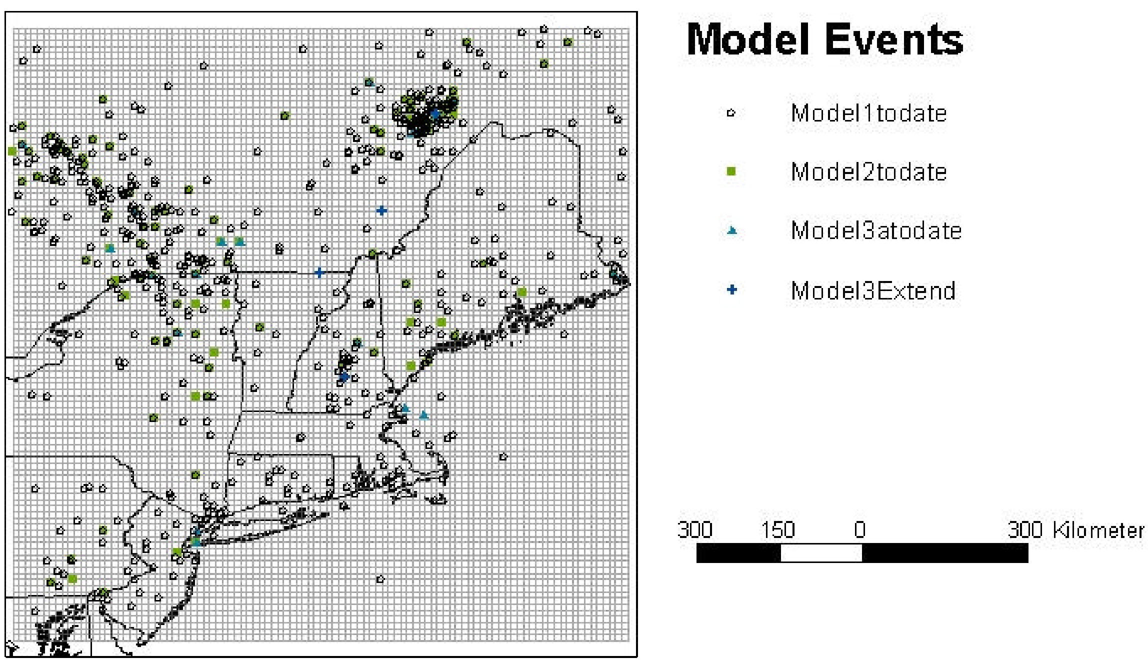
The most recent version of the National Seismic Hazard Maps, produced in 2002, included events through December 2001 (Frankel, et al 2002). The catalog for the 1996 maps, rather than the 2002 maps was available from the USGS website (USGS, 1996). Aside from a few minor modifications mentioned by Frankel, et al (2002), the only difference between the catalogs is the inclusion of events from 1996 to 2001. The USGS catalog was compiled from several national and regional catalogs with magnitudes converted to an equivalent body wave magnitude, m_b^*, a weighted sum of the available catalog magnitudes. With dependent events, like foreshocks and aftershocks, removed, the USGS catalog consisted of 2750 events of m_b^* 3.0 and greater between 1700 and 1995. (Mueller, et al, 1997)

The USGS catalog was supplemented by Northeastern United States catalogs available from Boston College's Weston Observatory in order to include New England earthquakes prior to 1700 and after 1995. The observatory's historic catalog includes events in New England and adjacent regions from 1568 though 1990 and uses Nuttli magnitude m_N, which is similar to m_{bLg} as its scale (Weston Observatory, 2002). A recent catalog was also available for events since 1991, although the data is less refined. Multiple magnitudes were reported and dependent events were not removed (Weston Observatory, 2003). The 1996 USGS catalog formed the basis for the catalog to be used in developing the New England seismic hazard maps. To this 10 events between 1638 and 1700 were added from the Weston historic catalog. The 1638 event believed by Ebel (1996) to have occurred in New Hampshire had its location adjusted to reflect the location suggested by Ebel, et al (2000) in central New Hampshire. The Weston Observatory's recent catalog provided 54 events of magnitude 3.0 and greater between January 1996 and April 2003. The recent events were checked against a list of recent events from the Lamont-Doherty Cooperative Seismographic Network (LDEO, 2003). These were listed based on their m_N magnitudes when available and by Coda magnitude, M_C otherwise. It was anticipated that the error from the use of Coda magnitude for a small number events near the magnitude thresholds for the models would be negligible.

The complete catalog for this study contained 2802 events, but was only acceptably complete for New England and surrounding areas, due to the limited coverage of the Weston catalogs. Therefore the source area had to be defined. A large source area was desirable because seismic waves travel well in stable crust and excluding the hazard from events beyond the source area could cause the expected ground motion to be underestimated, particularly near the boundaries of the source area. Expanding the source area to include regions with an incomplete catalog would result in similar errors. For convenience, a 10° longitude by 10° latitude area was used and centered so as to include all of New England, as much of surrounding regions of Quebec and New York as possible and include as little of the Atlantic Ocean as possible. The source area was defined between -77° and -67° longitude and between 39° and 49° latitude.

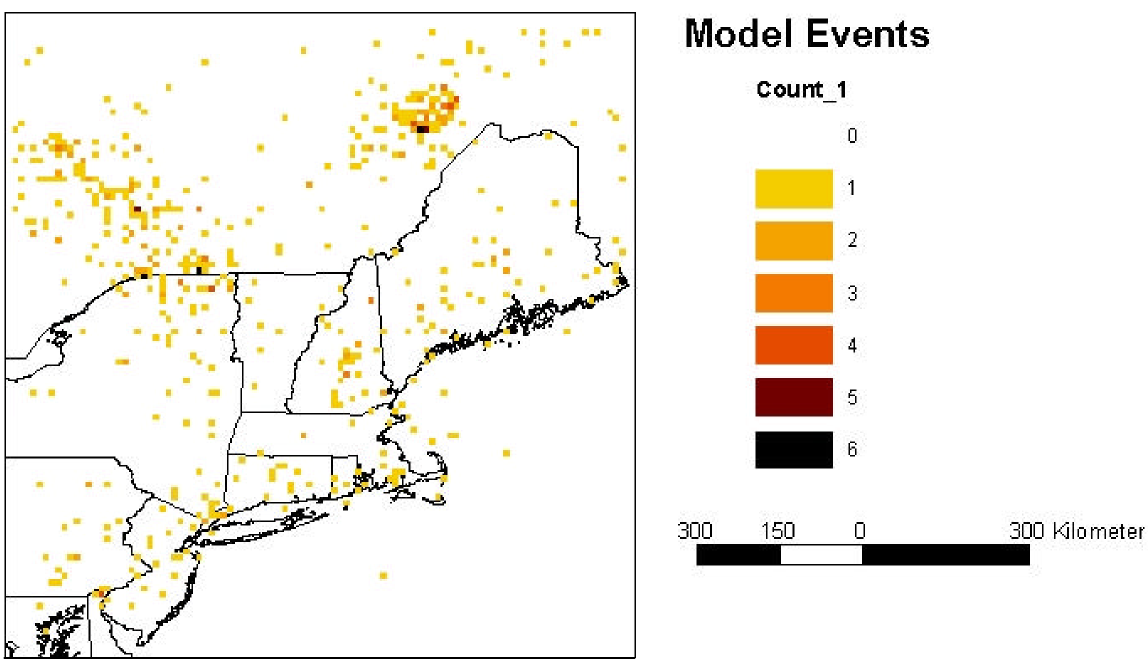
The cell counts for the spatially smoothed historic seismicity models were determined using GIS. A grid was constructed in AutoCAD consisting of a square array of 10,000 squares. Degrees Longitude and Latitude were used as the x and y axes, respectively and the squares were sized just under 0.1° by 0.1° to prevent overlap which would confuse the analytical abilities of GIS. This was imported to GIS in the same coordinate system and converted to a shape file consisting of a database of polygons. A point file was created that defined the coordinates of the midpoint of each cell. This point file was joined with the grid shape file to define the coordinates, also the longitude and latitude, of the midpoint of the grid as an attribute of the cell defining its location. Finally, the grid was shifted an incremental amount to the southwest because a large number of earthquakes were falling on the boundaries of the polygons and were either double counted or ignored by GIS.

Figure III-2. Events Included in Historic Seismicity Models



The grid defining the source area and the events selected for each historic seismicity model are shown in Figure III-2. Magnitude 3.0 and greater events since 1924, shown as pentagons, were selected for Model 1. The selection was exported as a separate database file. This was repeated for magnitude 4.0 and greater events since 1860 for Model 2 and magnitude 5.0 events were compiled for Model 3. These are shown as squares and triangles, respectively. Two versions of Model 3 were made: one including all events since 1700 to match the USGS procedure and one including all events since 1638 to be tested. The events added to make up the extended Model 3 catalog are shown as crosses. The database files for each model were joined to the grid to create a shape file with the number of events from the database within each cell. The grid cell count data for Model 1 is shown in Figure III-3. The counts for each historic seismicity model were exported to Excel to be manipulated by the VBA programs.

Figure III-3. Model 1 Raw Grid Event Count



A VBA subroutine was written to spatially smooth the raw counts for each model. For every cell, the subroutine calculates a new value for the cell count that is effectively an average of the raw cell counts for the surrounding cells within a certain radius weighted according to the distance to the original cell. The program simultaneously uses the longitudes, latitudes and counts of several cells. Therefore it was expedient to group the three parameters together in a single variable using a user defined variable type which was called "cell", consisting of three single-precision numbers to hold the three parameters used by the subroutine. A 100 by 100 array of "cell" variables was defined to correspond to the spatial positioning of the cell polygons on the maps.

The simplified input functions of VBA collected the coordinates and raw count for each cell and prompted the user for a correlation distance. This is the radius within which neighboring cells will influence a cell's count. A correlation distance of 50km was used for Model 1, while a correlation distance of 75km was used for Model 2 and Model 3 after Frankel, et al (1996). The selection of correlation is important to the quality of the maps. A correlation distance that is too small creates small circles of elevated counts around a cluster of events and may underestimate the risk in between clusters. Too large a correlation distance could obscure areas of higher seismicity by combining them with other areas. This might result in higher cell counts between areas of higher seismicity than in the actual peaks. (Frankel, et al, 1996)

The distance between the cells had to be calculated to determine if it was within the correlation distance. This required a function that calculated distance between the midpoints of two cells based on the longitude and latitude of the cell midpoints. The following was used:

D = 6378km *acos[sin(lat1)*sin(lat2) + cos(lat1)*cos(lat2)*cos(lon2-lon1)]

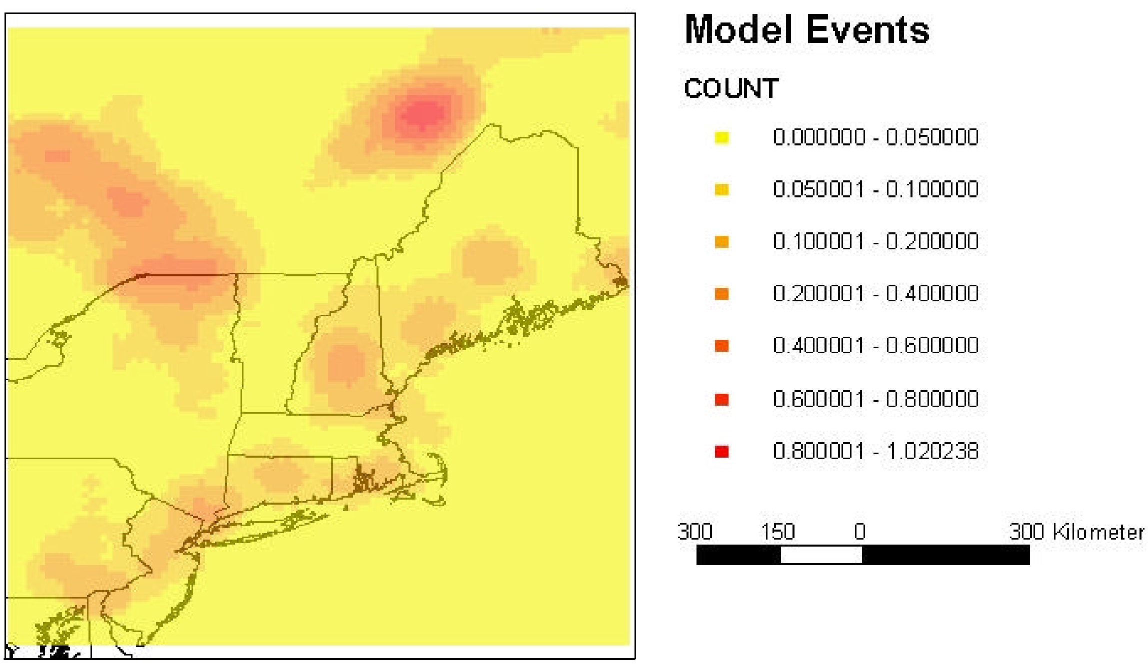
For this equation, longitude and latitude were converted from degrees to radians and the distance is in kilometers. (Meridian World Data, 2002) This equation was relatively straightforward to code, except for the absence of the arccosine function in VBA. Most Excel workbook functions are accessible to VBA programs using a special syntax. This provided an arccosine function, however, it sometimes failed to work in instances where the distance between cells was zero. In the seismic hazard calculation subroutine, a trap was required to estimate distance between cells on the same line of longitude. This fixed the problem with the Excel arccosine function and should have improved runtime marginally.

For each cell, the distance between it and every other cell was calculated. If the distance to another cell was less than or equal to the correlation distance, then the count for that cell would be included in calculating the smoothed count. Frankel (1995) used a Gaussian smoothing function below to calculate the count for each cell.

$$n_i = \frac{\sum_j n_j \cdot e^{\frac{-\Delta_{ij}^2}{c^2}}}{\sum_j e^{\frac{-\Delta_{ij}^2}{c^2}}}$$

The smoothed count for cell i, n_i, is therefore the sum of the raw count in cell j for all values of j, multiplied by the exponential term divided by the sum of the exponentials where Δ_{ij} is the distance between cell i and cell j and c is the correlation distance. This count was saved in an array variable using the same indices of the cell type variable so as to not corrupt the raw count. The counts were printed along with the cell's longitude and latitude on a new worksheet for use by the seismic hazard subroutine. The smoothed cell counts for Model 1 are shown in Figure III-4.

Figure III-4. Model 1 Smoothed Cell Counts



The seismic hazard analysis subroutine is run for each model and collects the cell coordinates and smoothed count and stores it in the same cell type variable as the smoothing application. The user is prompted for the time period and minimum magnitude of the catalog for the model and the seismic rate adjustment factor. The seismic rate adjustment factor, which accounts for catalog omissions and uncertainty in earlier earthquakes, adjusts the historic seismicity rate to the presumed "complete" seismicity rate. The subroutine loops through all 10,000 grid cells and calls a function that determines the PGA value at that location for which the probability of exceedance is 10% in 50 years. The function selects trial ground motions and checks the rate of exceedance against the probabilistic criteria.

The temporal distribution of events in each cell is assumed to be Poissonian. Therefore the rate of exceedance corresponding to a probability of exceedance over a specified time period can be found. Rearranging the formulation provided earlier:

$$P[\,N \geq n] = 1- e^{-\lambda_m t} = 10\% = 1- e^{-\lambda_m 50yrs}$$

$$1.10 = e^{-\lambda_m 50yrs}$$

$$-\ln(1.10) = \lambda_m 50yrs$$

$$\lambda_m = -\ln(1.10)/50yrs = 0.0021072103/year$$

The ground motion that satisfies this rate is found using a recursive function called “Check” that searches a specified interval for the correct rate. A recursive function is a function that calls itself and is a powerful tool in computer programming. The Check function defines an error term that is the difference between the desired rate of 0.002107/yr and the rate of exceedance for a trial ground motion.

When the function is called, an initial ground motion and increment, which is some power of ten, is passed to the Check function along with the cell’s coordinates. The ground motion, u, is set initially to zero, and the increment to unity. A loop then tests the exceedance rate of the sum of the initial ground motion and the increment multiplied by an index variable between 1 and 10. The error term will then be found and determine the next step. If the error term of a trial value is within a convergence interval of 0.000001/year, then the trial value is returned as the PGA for that cell. If the error term is negative, yet too large to be considered converged, the ground motion is smaller than required, therefore more likely to occur than required, and the function will step to the next largest trial value. If the error term is positive it means that the trial rate is less than required. The change in the sign of the error term from negative to positive indicates that since the current trial motion is too large and the previous too small, the correct value must fall in between. Therefore, the Check function backs up one step and calls itself, passing the lower value as the initial ground motion and the current increment divided by 10. Intervals of order of magnitude smaller than the previous are searched until the correct PGA value is located.

Suppose the correct value of PGA for a particular cell is 0.41g. Initially, integers one through 10 are checked. When u equal to one is checked, the sign change in the error function will be detected. Check will call itself recursively to search between zero and one with an interval of 0.1g. For u of 0.1 to 0.4 the error function will be negative, indicating that the value with the correct rate has not been reached. When u reaches 0.5 the sign of the error term becomes positive and the one hundredths decimal place will be searched between 0.4 and 0.5. At the first step of this interval, 0.41, convergence is reached and the value returned. The subroutine can then proceed to the next cell and repeat the process. Had more precision been required to converge on the correct rate, Check could have called itself to check the one-thousandth place digits.

The recursive check function is the most critical piece of the algorithm. It can find a PGA value far more efficiently and provides a greater chance of converging on a solution than a brute-force type of algorithm because it does not require the programmer to know the size and precision of the output values in advanced. If, instead of a recursive function, a brute-force function were implemented, starting at zero and stepping with an increment small enough to be expected to be sufficiently precise, the program would run less predictably. The runtime for a cell with a large expected PGA would be far greater than that for a smaller value. If greater precision than allowed were required for a certain cell, the program would fail. Recursive functions are not flawless, and great care must be taken to ensure that the function eventually returns a value, rather than calling itself infinitely. This was accomplished in the check function by providing a trap that would return zero if a ground motion was not found greater than 10^{-6}g.

A function called "Rate" was called to find the rate of exceedance for a trial ground motion in the Check function. Frankel (1995) used the smoothed historic seismicity to calculate the annual rate of exceedance for a ground motion, u_0 for a specific cell by taking a sum over distance and magnitude.

$$\lambda(u > u_0) = \sum_k \sum_l 10^{\left(\mathrm{Log}\left(\frac{N_k}{T}\right) - b(M_l - M_{ref})\right)} \cdot P(u > u_0 \cdot |D_k, M_l|)$$

This equation is a form of the ground motion annual rate of exceedance calculation for a probabilistic seismic hazard analysis as presented earlier. It is the sum over discrete magnitude and distance bins, using the indices k and l respectively, of the product of the annual rate of exceedance for distance k and magnitude l and the probability of a ground motion exceeding some trial value, u_0. The rate of exceedance is a form of Gutenberg-Richter recurrence law. The a value is the logarithm of the binned count divided by the catalog time period. This varies slightly from the typical definition of a in that the count is derived from a catalog with a minimum reference magnitude, M_{ref}. Since constant, a, is defined in terms of a reference magnitude, the magnitude term must include M_{ref}. Since the earthquake catalog is incomplete for events below M_{ref} for each model, the origin of the recurrence law is moved to $M = M_{ref}$ to use more complete data.

The b value in the recurrence law is independent of the magnitude used to calculate a. Frankel, et al (1996) found that regression of the CEUS catalog east of -105° longitude accounting for completeness periods for different magnitudes resulted in a b value of 0.96±0.2 which was rounded to 0.95. This b value was found to reflect the historic seismicity of m_b 5.0 and greater events when used with the a values in Model 1 and Model 2, thereby effectively constraining the procedure to this rate. Based on the work of others, Frankel, et al used a b value of 0.76 for a 40km by 70km ellipse around Charlevoix, Quebec. Since ground motions for Charlevoix were not of interest to this study and the area in which the lower b value was used was not defined, a constant value of b equal to 0.95 was used.

By defining the recurrence law in terms of binned historic seismicity, the source temporal model and source to site distance models are combined. Each distance bin is considered as a source and is represented by a common distance equal to the radius of the middle of the bin. To accomplish this a count variable is defined as an array of 50 values representing counts for bins within a distance of 10 km to 500 km. The distance between the cell representing the site in the hazard calculation and all other cells was calculated in the same manner as in the smoothing subroutine. Then for every cell, a loop cycled through distance bins and compared the bin range to the cell distance. The smoothed count for the cell was then added to the bin count corresponding to the distance bin in which the cell distance fell. This range was governed by limitations of the attenuation relations which were used. Another constraint was the source area of 10° by 10°, which corresponds to a rectangle with sides of the order of around 1000km. For most cells, bin counts for distances greater than a few hundred km were incomplete because the radius of the bin overlapped the boundaries of the source area. Large ground motions from events far from a site pose a substantially lower risk compared to events closer to the site. Therefore, neglecting events farther than 500km was expected to have a negligible effect on aggregate hazard and seemed a reasonable compromise that was favorable to run time as well.

Summing the rates of exceedance was performed using embedded loops that cycled through combinations of distance and magnitude. Three magnitude bins were used to consider events between m_{bLg} 4.5 and 7.5, represented by magnitudes of m_{bLg} 5.0, 6.0 and 7.0. This was selected based on the expected values of damaging earthquakes between $m_b = 4.5$ (Frankel, 1995) and M_{max} of M_w 7.5 from (Frankel, et al, 1996). This is also the range for which the attenuation relations were considered accurate.

It was previously mentioned that the seismicity rates for each model were adjusted to equal the rate for the time after which the catalog was considered complete. Frankel , et al (2002) made this adjustment by multiplying gridded seismicity by a seismic rate adjustment factor (SRAF)calculated by Mueller, et al (1997), equal to the presumed complete rate divided by the observed or “counted” rate. The complete rates for each model used for the national seismic hazard maps were the rate of events since 1976 for Model 1, 1924 for Model 2 and 1860 for Model 3. For the entire east coast of the United States, Mueller, et al applied seismic rate adjustment factors of 1.27, 1.15 and 1.58 to the historic seismicity of Model 1, Model 2 and Model 3, respectively. Larger factors were applied to Charlevoix and areas of Quebec north of the St. Lawrence River. For this study, the east coast SRAFs of Mueller et al (1997) were used for the entire source area. The rate was adjusted by multiplying the binned count by the seismic rate adjustment factors.

Model 4 is the background seismicity model that represents the hazard from moderate (m_b 5.0 to 7.0) earthquakes in recently inactive areas. The entire source area is treated as a uniform source zone (Frankel, 1995). Therefore the ground motion for every cell from this model is equal. Frankel, et al (1996) constructed this model by calculating the a value from all CEUS m_b 3.0 and greater events since 1924 adjusted to the post 1976 seismicity rate. They normalized this count by area and disaggregated so their seismic hazard code could be used without modification.

A slightly different approach was used for this study. The number of m_{bLg} 5.0 and greater events were counted since 1924 for the New England source zone. This reference magnitude was used due to the suggestion by Frankel (1995) that Model 1, which would use the same catalog as Frankel, et al's Model 4, underestimated the hazard of large events. Theoretically there should be no difference between the two approaches to Model 4 as only the origin of the data is being changed. The slope, b, remains equal to 0.95. These nine events were area normalized by dividing by 10,000 cells and the average cell area, which was estimated to be 88km^2. This normalized count represented the cell count. Since the count was constant for all cells, no smoothing was required.

The seismic hazard program was simplified to calculate the PGA for Model 4. PGA was calculated twice, rather than 10,000 times. The two ground motions were compared to ensure that they were equal, as expected. The distance bins were replaced with a function that multiplied the normalized cell count by a function that estimated the area of the bin. The procedure was otherwise the same and a constant ground motion of 0.04466g calculated for the source area.

The ground motion portion of the seismic hazard analysis was the same for all models. For every combination of magnitude and distance, the Rate function called the function PPGA that returned the probability of exceedance of the trial ground motion given magnitude and distance. This represents the second term of the rate of exceedance equation in the Rate function. PPGA found the weighted average of the probability of exceedance for each attenuation relation using the same ground motion, distance and magnitude parameters. It also converted magnitudes from m_{bLg} to M_w for attenuation relations requiring the later scale.

Magnitude conversion is required because the source catalogs use forms of body wave magnitude, m_b, m_b^* and m_{bLg}, while moment magnitude, M_w is preferred for developing attenuation relations. M_w is preferred because of it is based on physical characteristics of the source, rather than a filtered instrumental reading of the ground motion. When a body wave magnitude or other local scale is used, in effect the nature of the ground motion must be specified in order to determine the magnitude of event. (Boore & Atkinson, 1987) For example, the use of m_{bLg} implies that the seismic waves from the event in question are rich in Lg waves. Moment magnitude is based on seismic moment, which is a physical expression of the work done by an earthquake and is the product of the area of rupture, slip displacement and strength of the fault. Since it is based on energy release, rather than some portion of the waveform, seismic moment does not saturate or loose sensitivity to larger earthquakes. (Kramer, 1996) A one-to-one relationship exists between seismic moment and moment magnitude. Therefore, M_w maintains the physical basis and sensitivity to all events as seismic moment, making it the favored scale for developing attenuation relations (Johnston, 1996).

Frankel, et al (2002) used the m_{bLg} to M_w conversion of Boore and Atkinson (1987) and Johnston (1996) with equal weights to convert the catalog magnitude to that used by the attenuation relations. The Boore and Atkinson conversion is based on using station data from five historic events of m_{bLg} >5.0 to calculate the Lg magnitudes for the events using the original definition of Lg magnitude, which is defined below.

$$m_{bLg} = \begin{cases} 3.75 + 0.90 \text{ Log } (r/111) + \text{Log } (A/T) & 56\text{km} \; [\; r \; [\; 445\text{km} \\ 3.30 + 1.66 \text{ Log } (r/111) + \text{Log } (A/T) & 445\text{km} \; [\; r \; [\; 3336\text{km} \end{cases}$$

The site-source distance is r, the peak vertical ground motion in micrometers is A and the period of the peak motion in seconds is T (Boore & Atkinson, 1987). Usually the period band of the ground motion is restricted to some range of high frequency periods. A period of one second is frequently used. If periods between 0.3 seconds and 2.0 seconds are selected, the Nuttli magnitude, m_N, a special case of m_{bLg}, is defined. (Johnston, 1996) Boore and Atkinson used periods less than 10 seconds and were able to use all station data.

Boore & Atkinson used random process theory, along with various source scaling to predict the period and peak amplitude as recorded on standard instruments and converted to m_{bLg}. The predicted Lg magnitudes from the constant source-scaling model and the estimated moment magnitudes were plotted and a curve fit by least squares regression. For earthquakes of magnitude 4 [m_{bLg} [7 their conversion is:

$$M_w = 2.715 - 0.277\ m_{bLg} + 0.127\ m_{bLg}^2$$

Johnston (1996) used instrumental data from 177 worldwide stable crustal region (SCR) events between 1925 and 1994 with directly and indirectly determined seismic moments to relate seismic moment to teleseismic magnitude scales, m_b and Surface wave magnitude, M_s and regional scales m_{bLg} and Local (Richter) magnitude, M_L. Regression analysis was then performed on plots of the logarithm of seismic moment versus the alternative magnitude scales. This approach differs from Boore and Atkinson in that it is an empirical correlation rather than a stochastic model. Johnston assumes that events from nine SCRs can be combined as a heterogeneous data set and that differences between SCRs are much less than differences between SCRs and intraplate regions.

In calculating the correlation between seismic moment and Lg magnitude, m_{bLg} had to be defined. Johnston developed equations based on a period of 1.0 sec. 6 1.0 sec., as well as for the longer period band that was used by Boore and Atkinson. The difference in method of calculating m_{bLg} resulted in difference of the order of

m_{bLg} 0.2 to 0.4. Johnston found that conversions using different definitions of Lg magnitude agreed to within M_w 0.2 to 0.3 for m_{bLg} 4.5 to 6.5. The T ~ 1.0 sec regression below was used by this study.

$$\mathrm{Log}\,(M_o) = 17.76 + 0.360\, m_{bLg} + 0.140\, m_{bLg}^2$$

The definition of moment magnitude is:

$$M_w = \mathrm{Log}\,(M_o) / 1.5 - 10.7 \quad \text{(Kramer, 1996)}$$

Therefore, the conversion of m_{bLg} to M_w after Johnston (1996) is:

$$M_w = \frac{(2.715 - 0.277\, m_{bLg} + 0.127\, m_{bLg}^2)}{1.5} - 10.7$$

The m_{bLg} to M_w conversions of Boore and Atkinson and Johnston were used by Frankel, et al (2002), and for this study with equal weights.

The PPGA function returns the weighted average of the exceedance probabilities of the four attenuation relations for the trial ground motion bin distance and magnitude. Each attenuation relation was coded into functions of similar form that returned its exceedance probability. The function call in PPGA would pass the attenuation relation the trial ground motion, epicentral distance and magnitude in either m_{bLg} or M_w scale. The attenuation relation function would then calculate a mean PGA value and standard deviation for the distance and magnitude. PGA was assumed lognormally distributed and the Excel Lognormal Distribution Function was subtracted from unity to determine the probability of exceedance given the trial value and logarithms of the mean and standard deviation.

The attenuation relation of Atkinson and Boore (1995) was the only ground motion estimator used by Frankel (1995) and was utilized by Frankel, et al (2002) after not being used in developing the 1996 maps. It is an updated form of the attenuation relation presented in Boore and Atkinson (1987). It is an empirically based stochastic model, which uses data from the northeastern United States and southeastern Canada to provide parameters for the theoretical ground motion and wave propagation models. As a function of moment magnitude between 4.0 and 6.8 and source to site distance, the logarithm of PGA in cm/s^2 for rock sites is:

$$\text{Log PGA} = 3.79 + 0.298\,(M - 6) - 0.0536\,(M-6)^2 - \text{Log } R - 0.00135\,R$$

Atkinson and Boore fit a quadratic regression curve to their stochastic model to keep it simple for practical application, however, their data required a fifth order polynomial to properly describe the relationship. As a result the relation over predicts spectral accelerations for M_w less than 5.0 and greatly over predicts these events at a distance greater than 30km. At the same time it underestimates ground motions within 15km of the source. Atkinson and Boore compared their quadratic relation to the tabular "exact" relation for exceedance probabilities of 0.002 per year and 0.0001 per year. For expected PGA greater than 25%g, the quadratic and "exact" forms were within 5 or 10% of each other. For PGA in the range of 10%g to 20%g, the quadratic form over predicted but 20 to 40%. Expected PGAs less than 5%g were grossly over predicted.

Frankel, et al (2002) used the tabular form of Atkinson and Boore (1995) adjusted using site amplification for the velocity profile for the NEHRP BC boundary soft rock site condition. For this study, the quadratic form was used for computational efficiency and because it was available. The types of errors discussed previously could therefore be expected in the maps, especially in areas with low ground motions. The rock ground motion was adjusted to BC conditions using a site amplification factor. Frankel, et al (1996) used a factor of 1.52 to make the same adjustment to the attenuation relationship of Toro, et al (1994). Dividing the trial ground motion, which is intended to represent the soft rock motion, by the amplification factor, converts it to a hard rock motion so it can be compared to the probability distribution of the attenuation relation. The reported estimated exceedance probability is then associated with the initial soft rock ground motion The trial ground motion also had to be converted from %g to cm /s^2. A standard deviation was selected of 0.25 in base 10 logarithmic scale by roughly averaging the standard deviations given for several frequencies and moment magnitude scale. This does not account for uncertainty in converting from m_{bLg} to M_w, however, the uncertainty from this conversion was not explicitly considered for any other relations. Mean PGA and the standard deviation had to be converted from base 10 to natural logarithmic scales.

Toro, et al (1997) developed attenuation relations for spectral acceleration and PGA of central and eastern North America (CENA) based on a stochastic model of source excitation and a wave propagation model that considers multiple rays in horizontal layers of crust. Updating a previous relation used by Frankel, et al (1996), parametric and modeling uncertainty was quantified in greater detail. They developed models for 16 different areas with different sets of crustal parameters and found that 15 of these areas were similar. The outlier represented the coast of the Gulf of Mexico. Attenuation models were developed with coefficients corresponding to various spectral acceleration frequencies M_w and m_{bLg} scales for the Gulf coast and the rest of CENA.

Frankel, et al (1996) used the m_{bLg} version of the previous Toro, et al relation. The relation used by this study was the CEUS relation for median PGA using m_{bLg} scale. It is shown below.

$$\begin{aligned}\mathrm{Ln(PGA)} = {} & 2.07 + 1.2(m - 6) + 0\,(m-6)^2 - 1.28\mathrm{Ln}(R_M) \\ & + 0.05\,\mathrm{Max}[\,\mathrm{Ln}(R_M/100), 0] - 0.0018R_M + \varepsilon_e + \varepsilon_a\end{aligned}$$

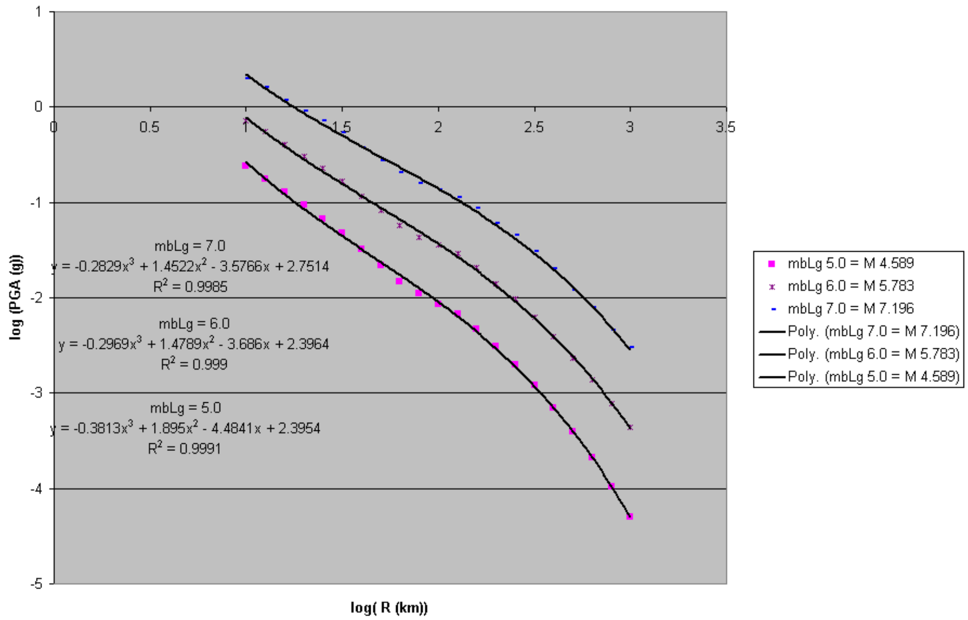
$$\text{where } R_M = \sqrt{(R_{jb}^2 + 9.3^2)}$$

R_{jb} is the site-to-source, or Joyner-Boore distance. The error terms ε_e represents epistemic uncertainty, or the effect of incomplete data and incomplete understanding of seismic processes. Aleatory uncertainty, or physical randomness is represented by ε_a. The error terms have magnitude and frequency specific standard deviations for modeling and parametric uncertainty. The relation is applicable to events between M_w 5.0 to 8.0 and distances between 1km and 500km. It was compared to data at rock sites within 200km of 18 mid-continent events of M_w 4.0 and greater and was found to be consistent with results from Boore and Atkinson (1987), Atkinson and Boore (1995) and others with comparable uncertainties.

The quantification of uncertainty of Toro, et al (1997) was not used for this study. A constant natural logarithmic standard deviation of 0.75 replaced the functions of magnitude distance and frequency. Frankel et al (1996) used this constant with the earlier Toro, et al relation. This standard deviation is actually larger than the log scale 0.25 used with the Atkinson and Boore relation. The trial ground motion was divided by 1.52 in order to convert from BC site conditions used for the maps to hard rock conditions of the attenuation relations, in agreement with the 1996 maps.

Frankel, et al (1996) developed an attenuation relation using a stochastic simulation and random vibrations. They interpolated logarithms of ground motions for BC site conditions from lookup tables of M_w versus base 10 logarithm of distance for M_w between 4.4 and 8.2 and distance between 10km and 1000km. Rather than use the tables and develop lookup and interpolation functions for this study, a mathematical form of the attenuation relation was developed. Log PGA versus moment magnitude was plotted for each site-to-source distance. The bin Lg magnitudes used by the seismic hazard analysis, m_{bLg} 5.0, 6.0 and 7.0, were converted to M_w using Boore and Atkinson (1987) and Johnston (1996) conversions. Log PGA was then found for each converted magnitude using the curves for each distance and plotted versus Log distance. Figure III-5 shows the regression curves that were used to estimate the Frankel regression for each converted bin magnitude. A regression of the three curves resulted in cubic polynomial predicting Log PGA for each bin magnitude versus distance, which was used by the attenuation relation function to determine probability of exceedance. No effort was made to quantify the uncertainty in the regression or magnitude conversion. A natural logarithmic standard deviation of 0.75 was used after Frankel, et al (1996).

Figure III-5. Frankel, et al (1996) Attenuation Relation



The fourth attenuation relation used by Frankel, et al (2002) and this study is the hybrid empirical ENA attenuation relation of Campbell (2003). The hybrid empirical method uses a ratio of stochastic or theoretical ground motion estimates to adapt an empirical relation developed in one region to another. Too few ENA strong motion records exist to develop empirical ground motion relations, however the availability of network data for smaller events allows the determination of seismological models to relate ground motions to earthquake source size and source-to-site distance as is done for stochastic relations. These point-source stochastic models are the basis of the other attenuation relations used in this study. They are more limited than empirical models in that they are usually inaccurate near the source, and since they are all based on common methods, their use may underestimate epistemic uncertainty by assuming the validity of the stochastic method. The hybrid model has improved the near source characteristics and is less sensitive to the seismological parameters of each region. (Campbell, 2003)

The hybrid empirical method requires the selection of a host region, which will provide empirical ground motion estimates for use in the target region with adjustment factors applied. The use of multiple host region relations allows quantification of epistemic uncertainty. Campbell used western North America (WNA) attenuation relations by Abrahamson and Silva (1997), Campbell (1997), Sadigh, et al (1997) and Campbell and Bozognia (2003). The host region empirical estimates have physically realistic geometric and anelastic attenuation characteristics up to 70km. Ground motions were estimated for rock sites, at distances of 1, 2, 3, 5, 7, 10, 20, 30, 40, 50 and 70 km for M_w between 5.0 and 8.2 in increments of 0.2.

To calculate adjustment factors to apply the empirical WNA ground motions to adapt them to ENA events, Campbell used point-source stochastic models to estimate median ground motions for both host and target regions. The ratio of ENA to WNA stochastic ground motion estimates scaled the empirical WNA estimates for use in ENA. To account for the limitation of the empirical motions to 70km, stochastic ENA ground motions were estimated for distances of 70, 100, 130, 200, 300, 500, 700 and 1000 km and scaled such that the stochastic and empirical median motions were equal for the same magnitudes at a distance of 70km.

By performing a nonlinear regression of the hybrid empirical and stochastic estimates, Campbell developed a relation for the natural logarithm of PGA with distance and moment magnitude.

$$\mathrm{Ln(PGA)} = 0.0305 + f_1(M) + f_2(M, R) + f_3(R)$$

Where:

$$f_1 = 0.633\,M - 0.0427\,(8.5-M)^2$$

$$f_2 = -1.591\,\mathrm{Ln}\,(R) + (-\,0.00428 + 0.000483\,M)\,R$$

$$f_3 = \begin{cases} 0 & R\ [\ 70\text{ km} \\ 0.683\,\mathrm{Ln}(R/70) & 70\text{km}\ [\ R\ [\ 130\text{km} \end{cases}$$

The natural logarithm of the standard deviation is the sum of terms expressing aleatory and epistemic uncertainty. Aleatory Uncertainty is:

$$\sigma_{\ln PGA} = \begin{cases} 1.030 - 0.0860\,M & M < 7.16 \\ 0.414 & M \geq 7.16 \end{cases}$$

Campbell provided a lookup table of epistemic uncertainty. A regression of the natural log of epistemic uncertainty with moment magnitude revealed it to follow the form of a fifth order polynomial. To avoid this, a constant, average value of 0.28 was used. The site condition conversion was applied in the same manner as to other attenuation relations.

Frankel, et al (2002) applied equal weights of 0.286 to the attenuation relations of Atkinson and Boore (1995), Toro, et al (1997) and Frankel, et al (1996). Due to its novel approach, a lower weight of 0.143 was applied to the hybrid empirical relation of Campbell (2003). The weights were applied to the exceedance probabilities directly so that one probability of exceedance was returned for each trial ground motion. With the seismic hazard procedure defined, the hazard calculation was run for all 10,000 cells for all models. Each program run required approximately 8.5 hours on a computer with a 1.7 GHz Intel Pentium 4 processor. The results from running each model were combined to develop the seismic hazard maps.

The weighted average of the PGA value for each model was used to develop the New England seismic hazard maps. Frankel, et al (1996) assigned Model 1 twice the weight of Model 2 and Model 3, however an adaptive weighting scheme was used to include Model 4, which prevented Model 4 from lowering the seismicity in active areas. If the a value from weighted historic seismicity for a cell was greater than the background source zone a value, then Model 1 would receive a weight of 0.5 while Model 2 and Model 3 would be weighted by 0.25. Model 4 would not be used. If the a value from Model 4 was larger than the averaged historic seismicity, then Model 1 would be weighted by 0.4 and the other models by 0.2.

The hazard calculations for this study were made for each model independently to facilitate checking with maps in Frankel (1995) and with plots of catalog events. It was impractical to perform the calculation using a composite a value, because it would have required the seismic hazard application to process multiple reference magnitudes, seismic rate adjustment factors and catalog periods. An alternative procedure would have required a values and b values adjusted to the reference magnitudes as parameters rather than a single smoothed count. The adaptive weighting scheme was therefore applied to PGA results in the same way that Frankel, et al applied it to recurrence parameters. PGA for all cells and all models were imported to an Excel spreadsheet and a conditional equation used to find the weighted average. This was repeated for each map. The Excel sheet was then carefully converted into a viable database file for import into GIS.

The databases containing the gridded ground motions were plotted spatially in GIS. Each record in the database became a point at the midpoint of the cell containing the PGA values for each model and the weighted average as attributes. Five event themes were produced from each database allowing PGA for each field to be plotted spatially as set of color-coded shapes. A square shape about the size of a grid cell was used with a semi-translucent graduated color scheme. Changes in color roughly marked the contour lines for 2.5%g, 5%g, 7.5%g, 10%g, 20%g and 27%g. Four sets of maps were made containing the weighted average PGA with a probability of exceedance of 10% in 50 years and the constituent models. Maps following Frankel, et al (2002) were developed using seismic rate adjustment factors of Mueller (1997) and using pure historic seismicity. Maps adding 17th century events to Model 3 were made using the same seismicity weighting schemes.

For error analysis, the average gridded PGA values were compared with corresponding gridded values from the USGS 2002 National Seismic Hazard Maps (USGS, 2002). The difference was taken between the USGS and calculated values and the average, maximum, minimum difference and standard deviation of the difference determined. The USGS (2002) values were plotted in the same manner as the calculated New England seismic hazard maps and the difference between the two plotted to make a series of error maps, to assist in analyzing the procedure and modeling assumptions. The graduated color scheme of the error maps produced contours of –1%g, +1%g, +5%g, +10%g and +20%g.

The comparisons of the maps produced in this study with the national seismic hazard maps from 2002 and earlier were used to evaluate the modeling assumptions and deviations from the procedure described by Frankel, et al (2002). Maps based on the SRAFs of Mueller, et al and using pure historic seismicity were compared with the USGS maps to determine the effect of SRAF selection. The effect of the extension of the earthquake catalog for Model 3 was likewise observed. The error maps could be used to examine the effect of neglecting the change in b value for Charlevoix and the potential error from excluding events beyond the source area in the hazard calculation. Comparing different editions of the maps provided a means for gauging the sensitivity to smaller catalog changes and the use of revised attenuation relations. The availability of plots of most of the individual models in Frankel (1995) provided a comparison of contours for each model with the maps in this study. This was especially useful for Model 4, where the procedure was unclear and a different reference magnitude and catalog used. Finally, by attempting to explain major changes in terms of known variations to the procedure, the effect of less transparent changes, such as programming errors, bin selection and the omission of Model 5, can be considered as a measure of the sensitivity and utility of the Frankel, et al procedure for custom applications such as this regional study.

IV. RESULTS & DISCUSSION

Comparison of the New England Maps with each other and with published USGS maps can allow the identification of the effect of the seismic rate adjustment factors (SRAF) and the inclusion 17th century events, as was tested in this study. Understanding the general difference between the USGS maps and New England maps can assist in evaluating the effect of variation in the seismic hazard analysis procedure, which can lead to recommendations for future endeavors. The gridded seismicity database from the USGS (2002) was utilized to provide the primary graphical and numerical comparisons with the results from this study. A plot of the 1996 national seismic hazard data was obtained from the custom mapping feature on the USGS website to provide an additional comparison of the maps in this study as well as to assess the effect of procedural changes made between 1996 and 2002. In addition, Frankel (1995) published maps of some of the constituent models in the USGS maps, which could be compared once procedural changes could be taken into account.

Frankel (1995) provided national seismic hazard maps for hard-rock PGA with a probability of exceedance of 10% in 50 year in cm/s^2, which roughly corresponds to the %g scale used in this study multiplied by 10. Maps were provided for four models that became Model 1, Model 3, Model 4 and Model 5 in later editions of the maps, as well as a weighted average of the models. Only Atkinson and Boore's (1995) attenuation relation was used for ground motion estimation. The catalog on which the analysis was based extended only to 1984 resulting in a b value of 0.9 where 0.95 was later used in later editions. Adaptive weighting was not used, but maps for the weighted average and "worst case" were provided. A seismic rate adjustment of 1.39 was used on Model 3. A maximum magnitude of 7.0 was assumed.

Figure IV-1. Model 1, Historic Seismicity

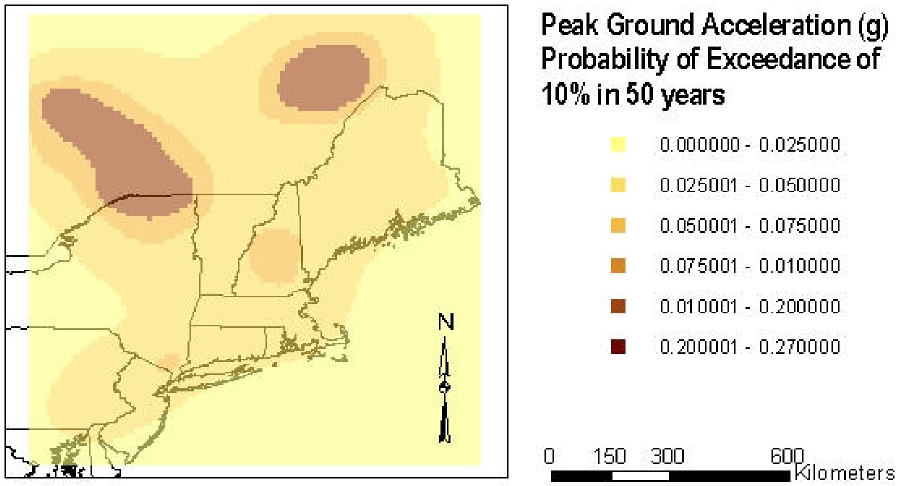


Figure IV-1 shows the seismic hazard map for Model 1 using pure historic seismicity (SRAF = 1.0). Most of the source area is within a 2.5%g contour that follows the Atlantic coast from New Jersey to Eastern Maine, breaks north, circling peak areas near Charlevoix and from the northern Adirondacks into Quebec, and then extends south around the Catskills, Poconos and Southeastern Pennsylvania. Contours of 5% circle the peaks in Quebec, as well as an area north of New York City and much of central New Hampshire.

The corresponding plot from Frankel (1995) is shown in Figure IV-2. Frankel's Model 1 is for rock sites and must be multiplied by the site amplification factor, 1.52, to correspond to the NEHRP BC soft rock conditions, according to Frankel, et al (1996). The same general patterns are found, but the values differ significantly. The $50cm/s^2$ contour (approximately 7.75%g for soft rock) follows the same general trend as the 2.5%g contour in Figure IV-1, excluding more of eastern

Maine, the New York capital district, northern Berkshires and southern Green Mountains, as well as a region near the convergence of the New Hampshire, Maine and Quebec border. The peaks in Quebec and New Hampshire appear to follow similar shapes, but are slightly higher. The peak in southern New York is larger in Figure IV-2, extending from northern New Jersey to Hartford, Connecticut. The Model 1 maps seem to show some sort of a skew resulting in considerably lower PGA values in this study. The soft rock ground motions should be larger than the hard rock motions of Frankel (1995) by a factor of 1.52. Instead the values on Figure IV-1 are lower by approximately 5%g, considering the BC site conditions, which is up to 200% error.

Figure IV-2. Model 1 from Frankel (1995)

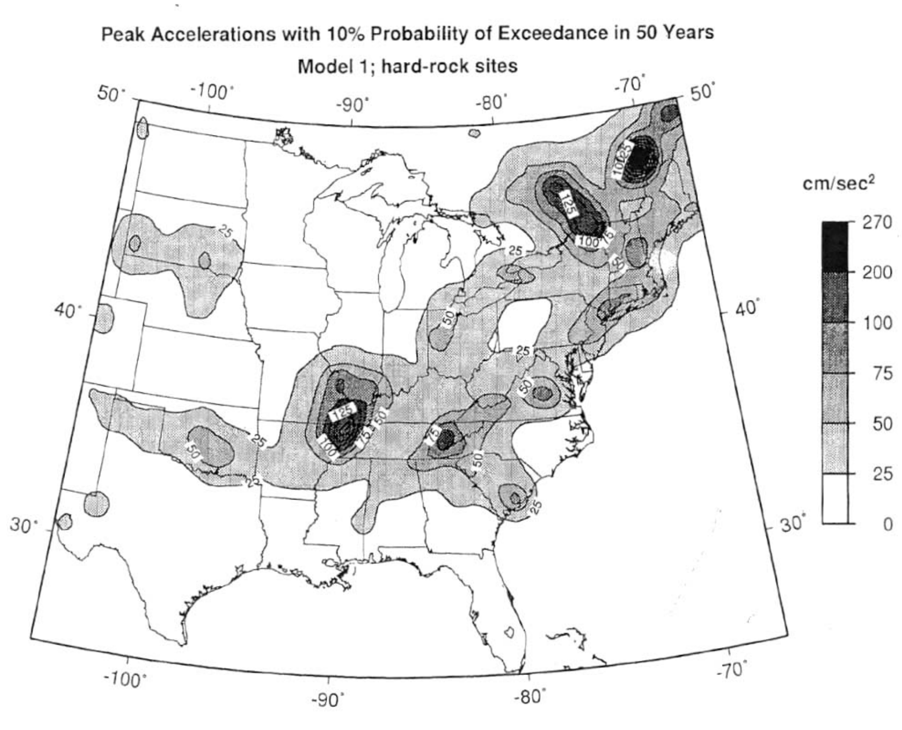


Figure IV-3. Model 1, Adjusted Historic Seismicity

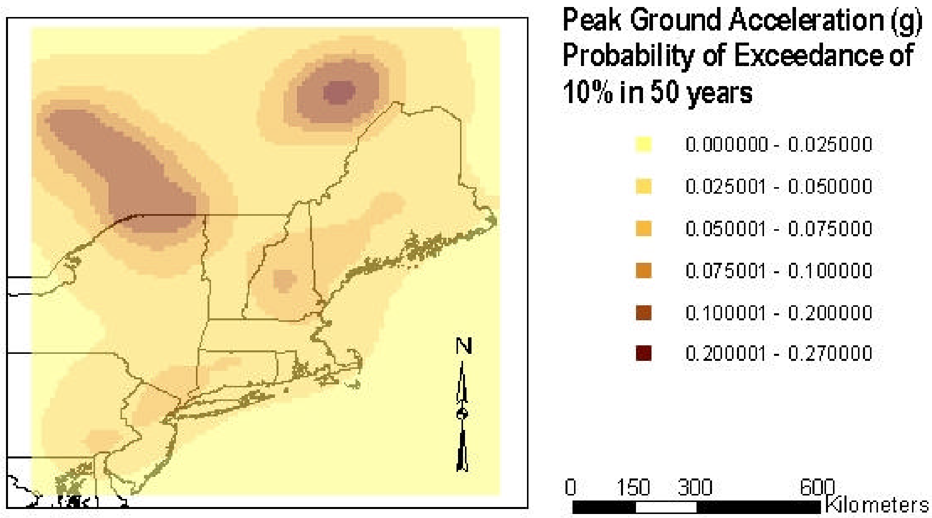


Figure IV-3 is the Model 1 map with a SRAF of 1.27 per Mueller, et al (1997). The peak areas in this figure are expanded and appear to be of magnitudes between Figure IV-1 and Figure IV-2, which is Model 1 from Frankel (1995). This suggests that Frankel did not use adjusted seismicity for Model 1 and that another procedural difference affects these maps. An obvious explanation is the tendency of the Atkinson and Boore (1995) attenuation relation to over predict ground motions below 5%g (hard rock) by well over 40%. The size of the difference between Model 1 for this study and Frankel suggests, however, that this is unlikely to be the cause of the entire difference. Frankel, et al (1996) reported that ground motions decreased by 2-3 times between the 1996 maps and previous editions due to reevaluation of magnitude-intensity conversion for historic earthquakes which were found to over-estimate the magnitude of M_w greater than 4.9 from maximum intensity. This explanation would be viable were it not for the fact that Model 1 counts all events greater than m_b^* 3.0 equally. If the catalog were the source of the difference, than the contours would be expected to vary more. This would suggest smaller details are cause, such as magnitude and distance binning, or standard deviation used on the attenuation relation.

Figure IV-4. Model 2 Historic Seismicity

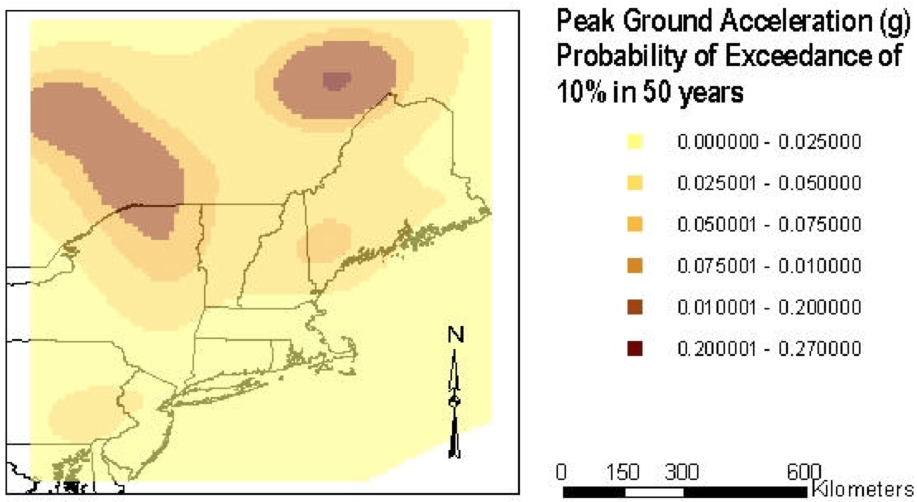
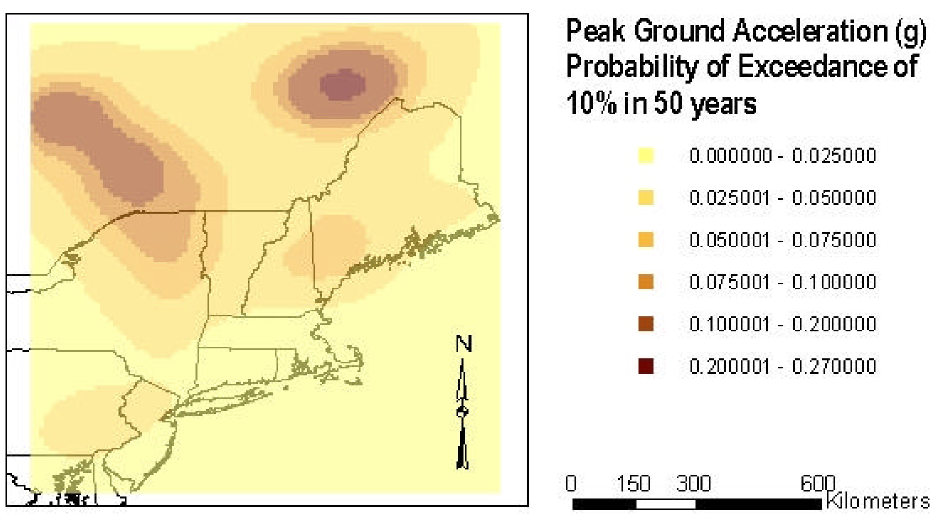
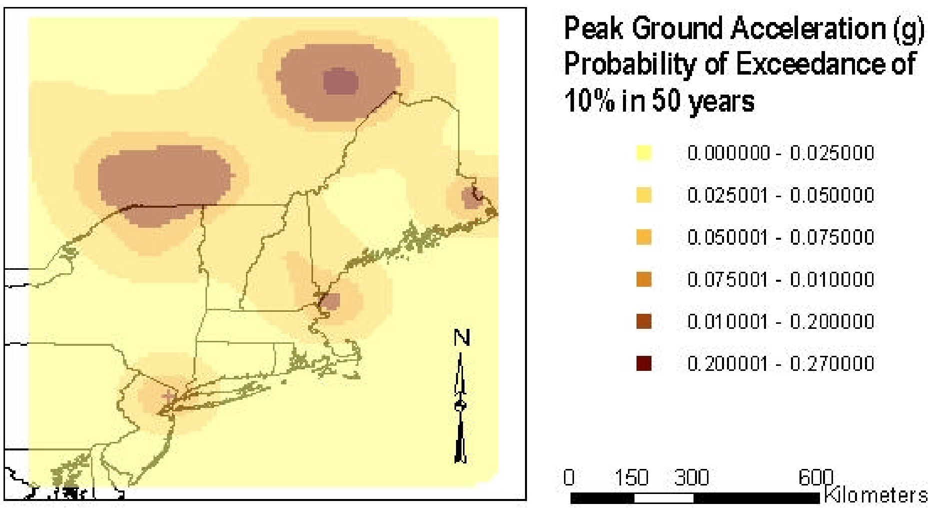


Figure IV-5. Model 2 Adjusted Histroic Seismicity



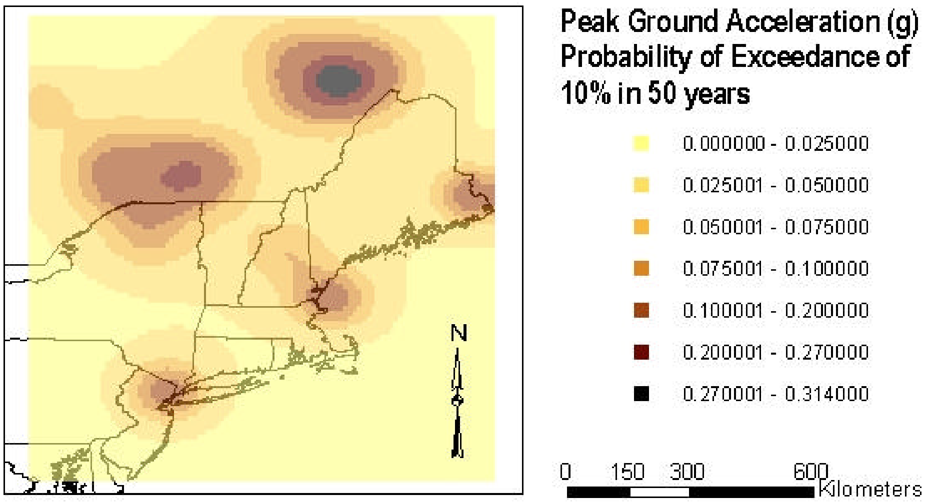
Model 2 was not used by Frankel (1995) and is shown in Figures IV-4 and IV-5 for SRAFs of 1.0 and 1.15, respectively. The 2.5%g contour in Figure IV-4 shows similar peak areas in Quebec as Model 1, but the 2.5%g contour traces north of Massachusetts's northern border as it southern extent, rather than the coast, indicating that much of the seismicity in southern New England and New York may have been smaller events. Eastern Maine also shows lower PGA values. The peak area in southern New York is gone and the New Hampshire peak is shifted east to an unusual cluster of events of m_b^* 4.0 to 4.9 north of Portland, Maine. Figure IV-5 shows the same trends with contours expanding slightly with increasing PGA as if scaled due to the SRAFs. The rationale for adding this map appears to be related to the difference in the shape of this map compared to Model 1 due to the unique distribution of some Model 2 events, as shown in Figure III-2.

Figure IV-6. Model 3, Historic Seismicity



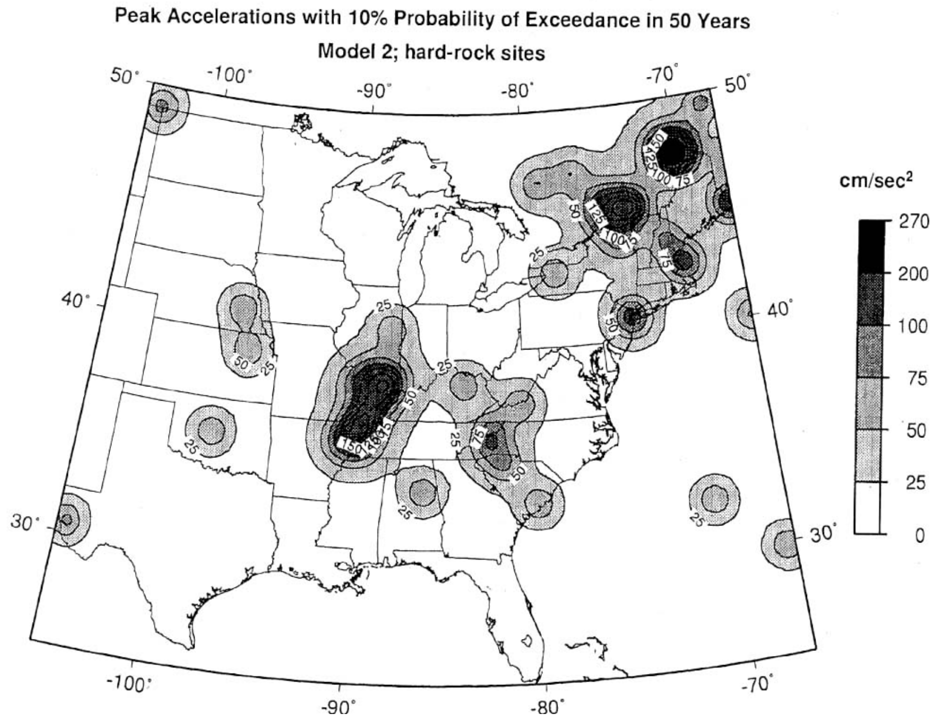
Model 3 results for SRAFs of 1.0 and 1.58 are shown in Figures IV-6 and IV-7, respectively. The equivalent model in Frankel (1995) is Figure IV-8 and used a SRAF of 1.39. If it were assumed for simplicity, that the effect of the site condition conversion and the attenuation relation canceled each other, one would expect the PGA values on Figure IV-8 to fall between those in Figure IV-6 and IV-7 based on the SRAF. Although the general trends are consistent among the maps, this is not the case. The Frankel PGA values are higher than those with a higher SRAF. Peak areas between Charlevoix, northern New York and New Hampshire are joined within a contour of 50cm/s^2 in Figure IV-8, where gaps between 2.5%g and 5%g exist in the other maps. Similarly, the maps from this study show a peak area above 2.5%g near New York City separate from the area above the same PGA including most of New England. The 2.5%g contour does not extend as far offshore as in the Frankel map.

Figure IV-7. Model 3 Adjusted Historic Seismicity



The difference in Model 3 from Frankel (1995) and this study seems to directly parallel the differences found in Model 1. This would suggest that some aspect of the procedures, other than the site condition, attenuation relation or SRAFs has the greatest effect on the value of PGA. A skew of 2.5% g is present when Figure IV-6 and Figure IV-8 are compared accounting for site condition and attenuation relation. The skew appears smaller and perhaps more localized when Figure IV-7 is compared, to Frankel. This also provides no evidence to suggest that Frankel (1995) utilized a catalog with suspect historic intensity-magnitude conversions.

Figure IV-8. Model 3 from Frankel (1995)



A major concern of this study was to develop a source area that would be sufficiently large to insolate the results from the effect of excluding events beyond the source boundary. Since model 3 has the fewest number of events, the maps are not as smooth, and for the first time, this effect is observable. Peak areas offshore at the southeast corner of the source area and near Buffalo, New York are missing, significantly lowering PGA in these areas. Underestimation of risk from events beyond the source area may also lower PGA in Eastern Maine due to its proximity to Miramichi, New Brunswick, beyond the source area. The addition of two m_b^* 5.0 and greater events within the source area since 1984 does not, however, appear to significantly affect the results.

Figure IV-9. Model 4, Background Seismicity

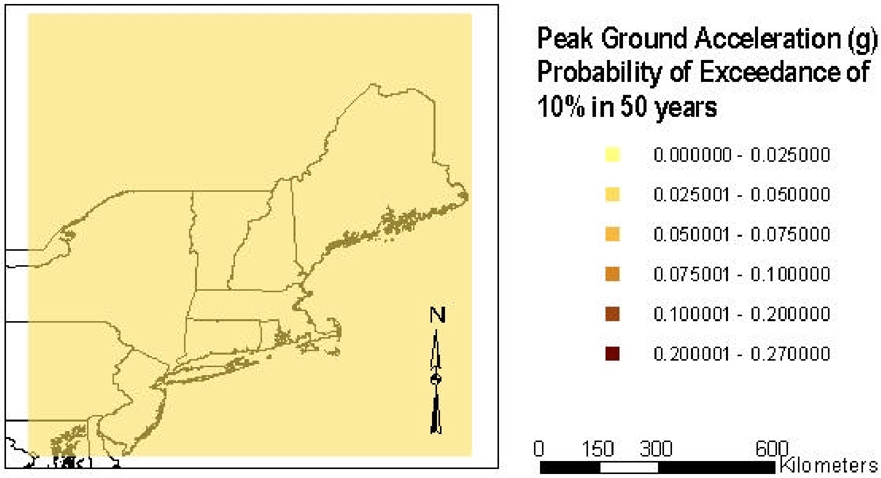


Figure IV-9 is the plot of the background seismicity model, Model 4. This model determined a single value based on distributing magnitude 5.0 and greater events since 1924 equally. A constant PGA of 4.466%g was calculated. Frankel (1995) used approximately 3%g for the background source. When this value is multiplied by the site amplification factor from Frankel, et al (1996), these values are equivalent. The agreement of these two models is remarkable considering the differences found in other models, however, it is not entirely clear how Frankel (1995) developed his background model. The Model 4 from this study was not consistent with Frankel, et al (1996) in that magnitude 5.0, rather than 3.0 was considered the reference magnitude. The time period of the catalog was the same. If the seismicity of the source area since 1924 closely follows a Gutenberg-Richter attenuation relation, that is, the logarithm of the annual exceedance rate varies linearly with magnitude, then the results should be equivalent. If significant scatter is found in the data, the model may be shifted up or down the Log λ_m axis as the slope is held constant using a constant b value. Figure IV-10 shows this shift of the recurrence rate when the reference magnitude is changed from 3.0 to 5.0 for a square kilometer of the source area. The shift is small on a logarithmic scale, but the intercepts of the recurrence laws are separated by approximately 10 events/year. This means that the Mref = 5.0 recurrence model predicts approximately 10 additional events per year of all magnitudes, confirming the concern that a background model based on a reference magnitude of 3.0 could under predict the risk of larger events. If it is again assumed that the difference in site condition and ground motion estimation produce counteracting effects, then Frankel's background model is much lower than that of this study as has been observed in other models. This suggests that the unexplained difference between this study and Frankel (1995) is inherent to the calculation because it effects both historic and background seismicity models.

Figure IV-10. Comparison of Model 4 Recurrence Laws Developed with M_{ref} of 3.0 and 5.0

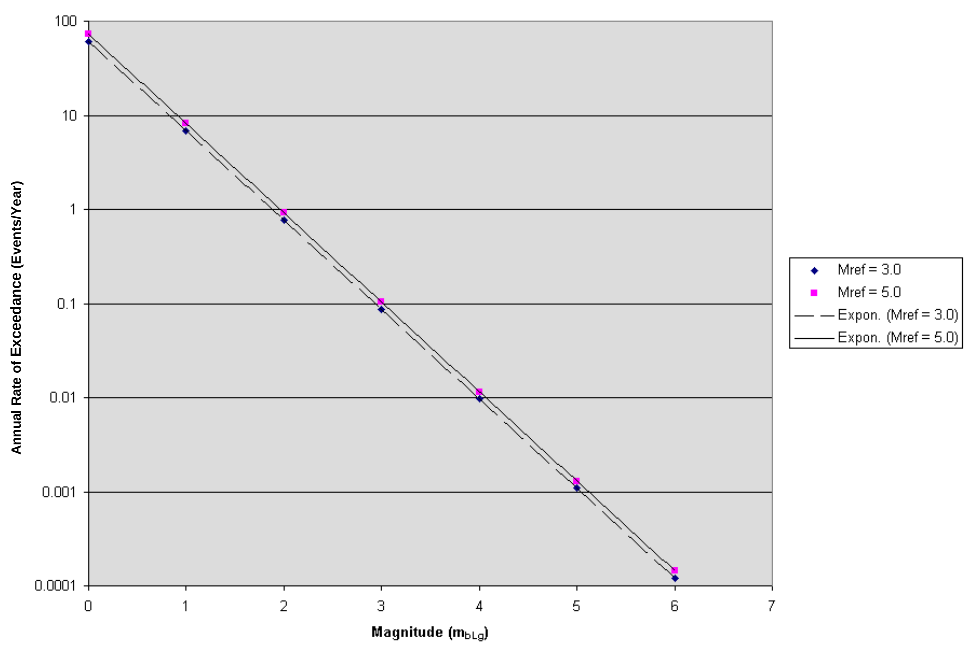


Figure IV-11. Total Seismic Hazard, Historic Seismicity

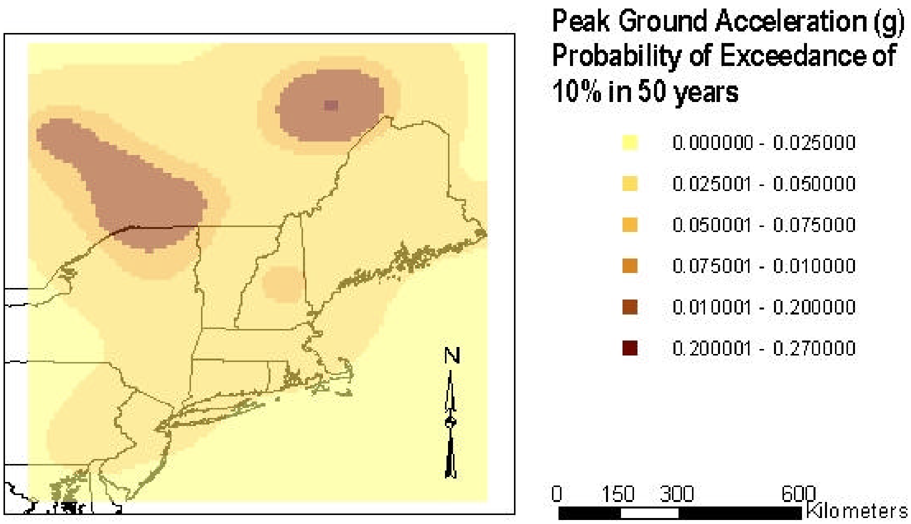
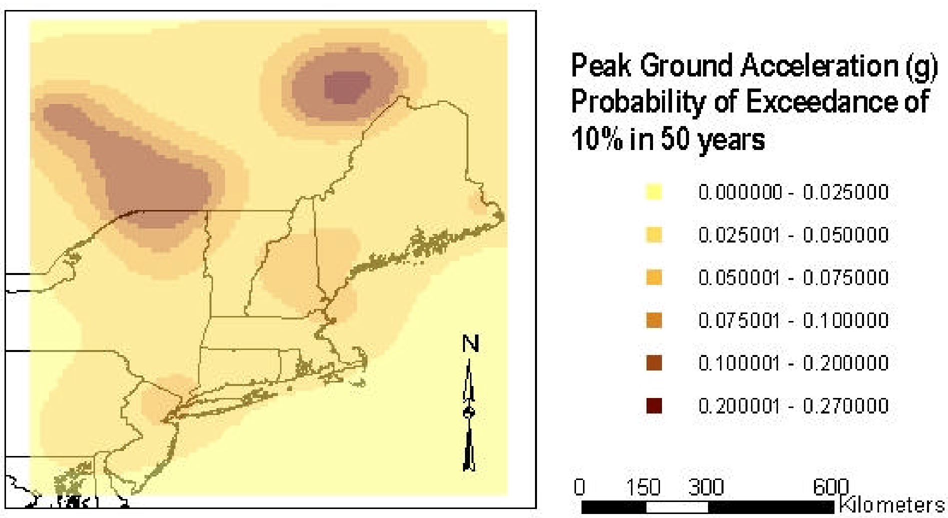


Figure IV-12. Total Seismic Hazard, Adjusted Historic Seismicity



The comparison of the single-model maps of Frankel (1995) and this study is difficult due to the procedural differences in generating the maps, particularly the difference in site condition. A much more straightforward comparison can be made with the 2002 National Seismic Hazard map because the procedures for hazard calculation used in this study were based on those used to develop the 2002 USGS maps. This comparison may be more difficult to interpret, however, because the effect of individual models is obscured. Figures IV-11 and IV-12 are the total seismic hazard maps for New England calculated in this study for SRAF of 1.0 and with SRAFs used after Mueller, et al (1997), respectively. Figure IV-11 looks remarkably like Figure IV-1 of Model 1. This is somewhat expected, as Model 1 receives a double weight compared to the other models. The total hazard differs primarily in the extension of the 2.5%g contour to cover all of eastern Maine, the reduction in size of the New Hampshire peak and elimination of the southern New York peak. The increase in PGA is likely due to the use of the background model, while the decreases may be the effect of Model 2, which lacks these peaks. Figure IV-12 lacks the same resemblance to the map of Model 1 with a SRAF applied. The 2.5%g contour is similar to Model 1, however the peaks better reflect Model 3. The New York peak is almost circular, as it is in Model 3. The New Hampshire peak has two elliptical lobes stretching from central New Hampshire. One extends southeast towards Cape Ann like Model 3, while the other is oriented eastward in to Maine resembling Model 2. Despite Model 1 being doubly weighted, the effects of Model 2 and Model 3 are visible.

Figure IV-13. Total Seismic Hazard. USGS (2002)

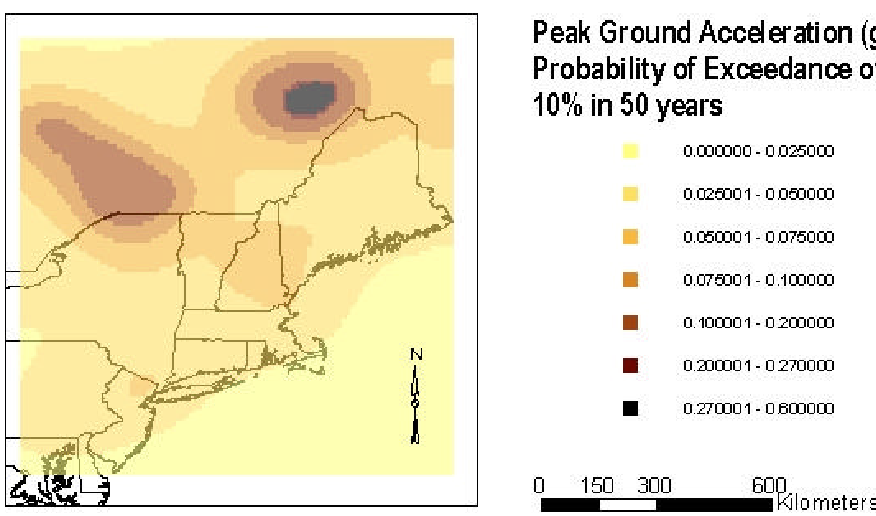
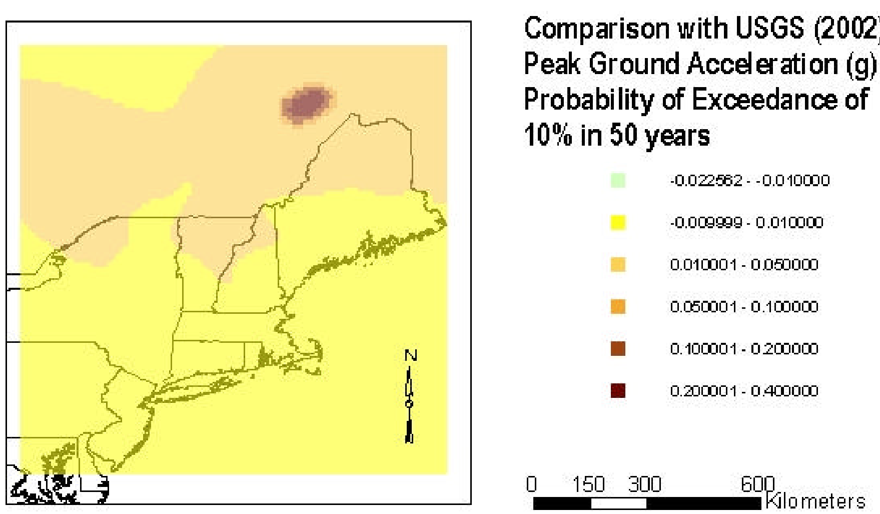


Figure IV-13 is a plot of the 2002 gridded PGA values from the National Seismic Hazard Maps for the points used in this study. As would be expected, this plot bears a closer resemblance to the total seismic hazard calculated with SRAFs from Mueller, et al, since these were used by the USGS for the 2002 maps. The New York and New Hampshire peaks exist, although they are smaller than on Figure IV-12. The New York peak is smaller in radius. The 5%g contour of the New Hampshire peak does not extend as far east or southeast as in Figure IV-12, but extends northwest to connect with the northeast-southeast peaks from the northern Adirondacks into Quebec. The peak area is connected to the Charlevoix peak by an area between 5%g contours. The Charlevoix peak has a large area of PGA greater than 27%g, which is not shown on Figure IV-12. The USGS map lacks a peak at Passamaquoddy Bay, Maine. The general trend is that the New England maps slightly overestimate PGA in the southern portions of the map and underestimate PGA in the northern parts of the source area.

Figure IV-14. Comparison of Total Hazard Maps with USGS. HIstoric Seismicity



The differences between the USGS 2002 gridded PGA values and the cell values used in creating each of the New England total seismic hazard maps for this study were calculated and plotted. Figures IV-14 and IV-15 are plots of the difference between Figure IV-13 and IV-11 and between Figure IV-13 and IV-12, respectively. Figure IV-14 supports the observation that the southern part of the map is more accurate. Most of the map shows a difference of ±1%g. This interval will be judged effectively “accurate”. Most of the United States portion of the map is within this interval, with the exceptions being New York between the Adirondacks and Lake Ontario, northern Vermont, the Upper Connecticut River Valley Coos County New Hampshire and most of Northern Maine. Most of Quebec shows an error of 1%g to 5%g, except the northwest corner of the map, which is lower, and the Charlevoix region, which show errors as high as 40%g.

Figure IV-15 shows the same general trend, but with some significant differences. Over 75% of the map is within the “accurate” interval. PGA is overestimated by as much as 2.25% off Cape Ann, Massachusetts, on the New York-Quebec border and in the New York metropolitan area. Patches of Quebec and Ontario fall in the +1%g to +5%g region, especially in the northeast corner of the map. Charlevoix again shows very high under predictions. Interestingly, it is surrounded by an “accurate” region, which is surrounded by +1%g to +5%g error.

Figure IV-15. Comparison of Total Hazard Maps with USGS. Adjusted Seismicity

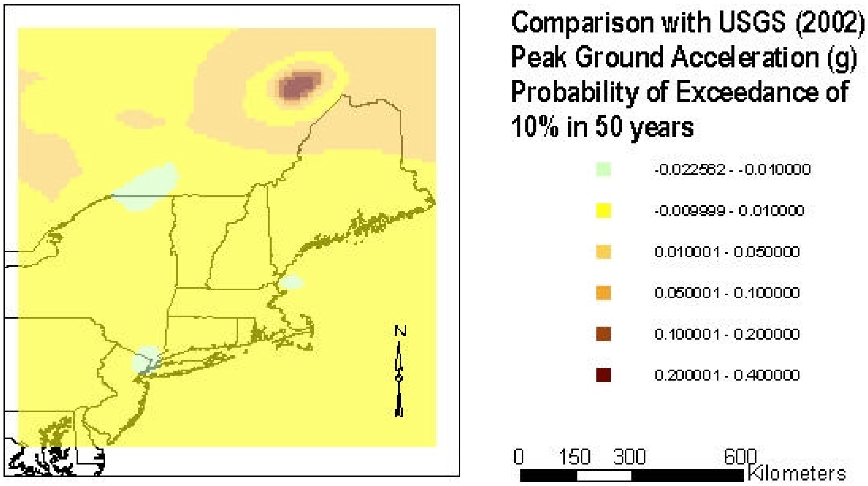
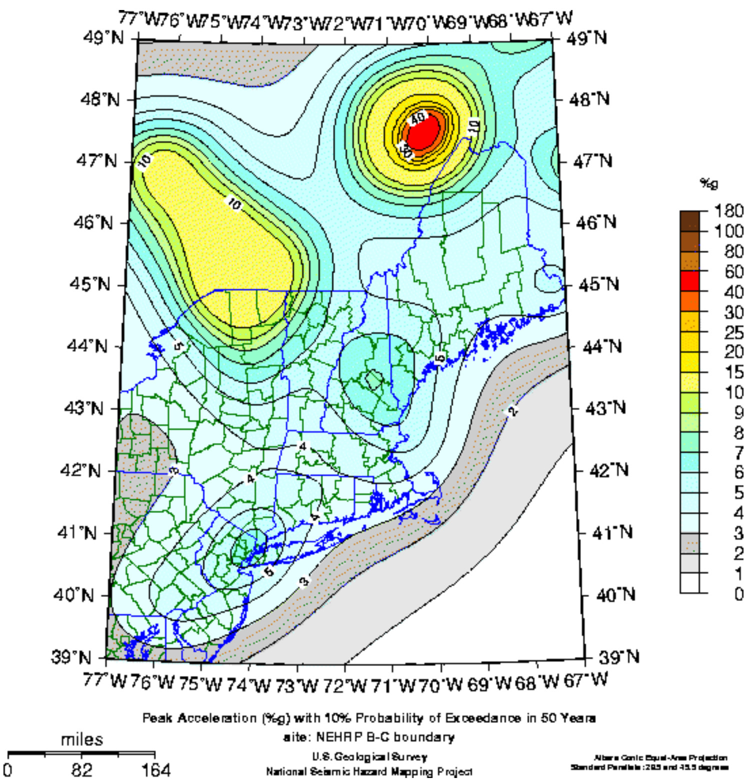


Figure IV-16. USGS (1996a) Total Seismic Hazard



Before attempting to analyze the trends in the total hazard maps and error maps, it would be helpful to compare the 2002 USGS maps with earlier versions of the same process. This comparison will provide a measure of the effect of modeling changes over subsequent hazard calculations and may be used to support or deny suspected sources of differences between the New England maps and USGS maps. Figure IV-16 is the plot of PGA with 10% probability of exceedance in 50 years from the 1996 maps (USGS, 1996a). The shape of the maps is the same between 1996, as shown by Figure IV-16, and 2002, as shown in Figure IV-13. Closer inspection reveals some possible scaling of PGA between map editions. The 2.5%g contour along the coast in 2002 is almost exactly the same as the 3%g contour in 1996. The area within the 5%g contour extending southeast from Quebec and New York through Vermont New Hampshire and northeast Massachusetts is larger in 1996 than in 2002. Similarly the peak near New York City is larger by about 1% g in 1996 compared to 2002. The primary procedural differences between Frankel, et al (1996) and Frankel, et al (2002) is the revision of the Johnston (1996) magnitude conversion from a pre published quadratic to the published version and the supplementation of the Frankel, et al (1996) attenuation relation with an updated, but similar Toro, et al (1997) relation, Campbell (2003) and Atkinson and Boore (1995). The catalog period was extended from the end of 1995 through the end of 2001, but this appears to have had little effect on the contour shapes. Although Atkinson and Boore's attenuation relation is expected to over predict ground motion of the scale seen in New England, the net effect appears to be a decrease in PGA between 1996 and 2002 editions of the USGS maps, ostensibly due to the Campbell and revised Toro, et al relations.

Figure IV-17. Total Seismic Hazard. Frankel (1995).

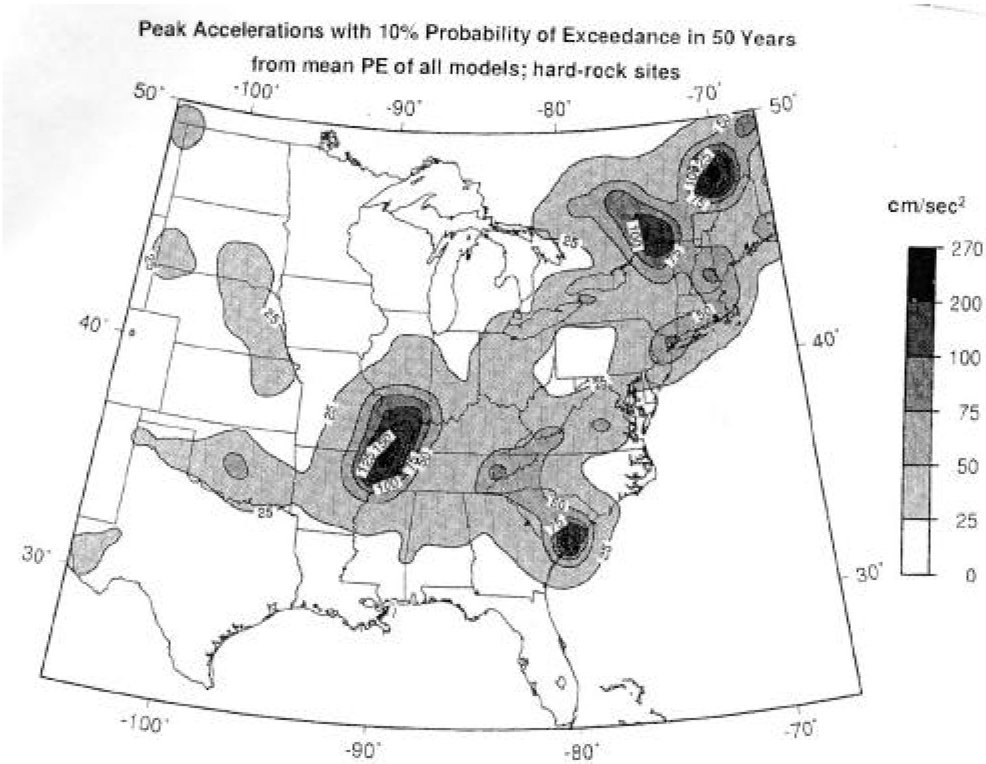
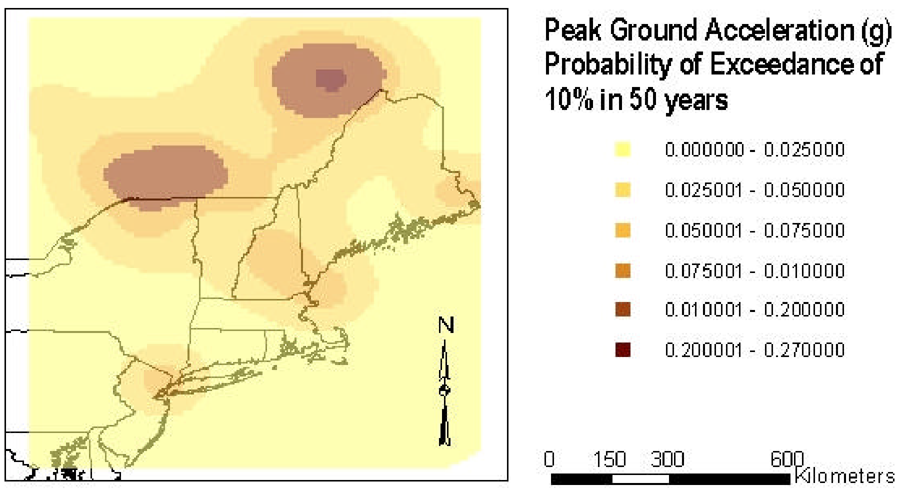


Figure IV-17 is a map of the weighted average of what in later maps were Model 1, Model 3 and Model 4 from Frankel (1995) for hard rock sites. Although the site conditions and ground motion estimates for the maps on Figure IV-17 and Figure IV-16 are different, the contours are remarkably similar. The 5% g contour on Figure IV-16 and the 50cm/s2 contours on Figure IV-17 are almost identical, with significant differences only in northeastern Maine, eastern Massachusetts and surrounding New York City. Slightly larger areas within 7.5% g are found on the 1995 map in New Hampshire, southern New York and extending from northwest corner of the map into Vermont. The ground motions therefore appeared slightly scaled between the 1995 and 1996 map with some minor shape differences. If it is assumed that the addition of Model 2 primarily affects the shape of the contours, then it would appear that the over prediction of the Atkinson and Boore attenuation relation is of a similar magnitude as the site amplification factor to convert from hard rock to soft rock conditions. Figure IV-5, which shows the adjusted seismicity Model 2 suggests that the decrease in PGA in Massachusetts and southern New York, the largest differences in contour shape between the 1995 and 1996 maps are likely the effect of the addition of Model 2. The addition of 10 years worth of events to the earthquake catalog shows a negligible effect.

Figure IV-18. Model 3 Historic Seismicity including 17th Century



Catalog changes between 1984 and 1995 and between 1996 and 2001 were not observed to significantly change the National Seismic Hazard Maps between 1995, 1996 and 2002. Including the events of the 17th century in the catalog for Model 3 involves adding 62 years to the earthquake catalog, rather than five to ten years, and would be expected to impact the shape of the maps. Figure IV-18 is the map of the extended catalog Model 3 with no seismicity adjustment, which would replace the Model 3 shown in Figure IV-6. Contour changes are obvious. The Quebec-New York border peak extends farther east and connects to the Charlevoix peak at PGA greater than 5%g. The 5%g area between Ossipee, New Hampshire and Cape Ann, Massachusetts is extended to the Connecticut River valley, but looses an area greater than 7.5%g off Cape Ann. Similarly, the peaks around New York City and Passamaquoddy Bay, Maine are reduced. Adding three events from the 17th Century increases PGA significantly near the events, but decreases PGA in other areas by adding years to the model's period. Figure IV-19 is the modified Model 3 with a SRAF of 1.58. Comparing this to Figure IV-7 reveals the same trends as when the SRAF is unity.

Figure IV-19. Model 3. Adjusted Historic Seismicity Including 17th Century

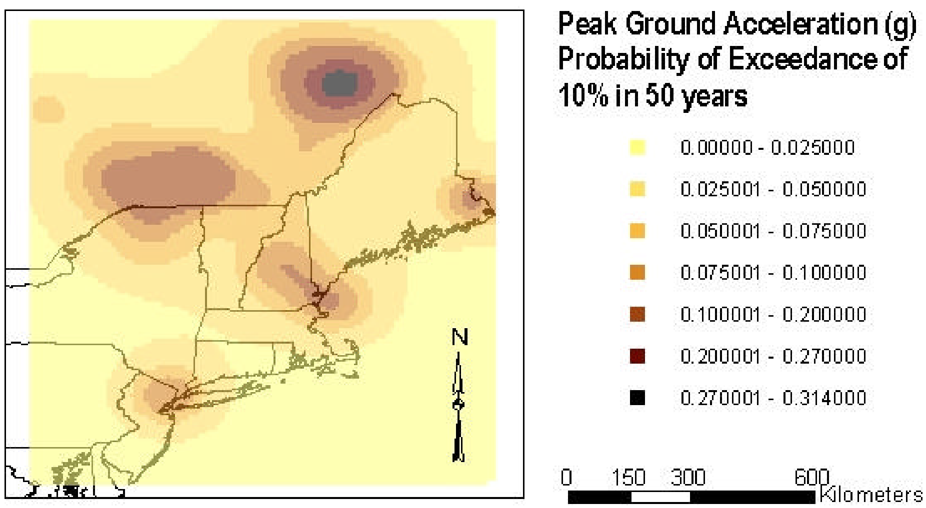
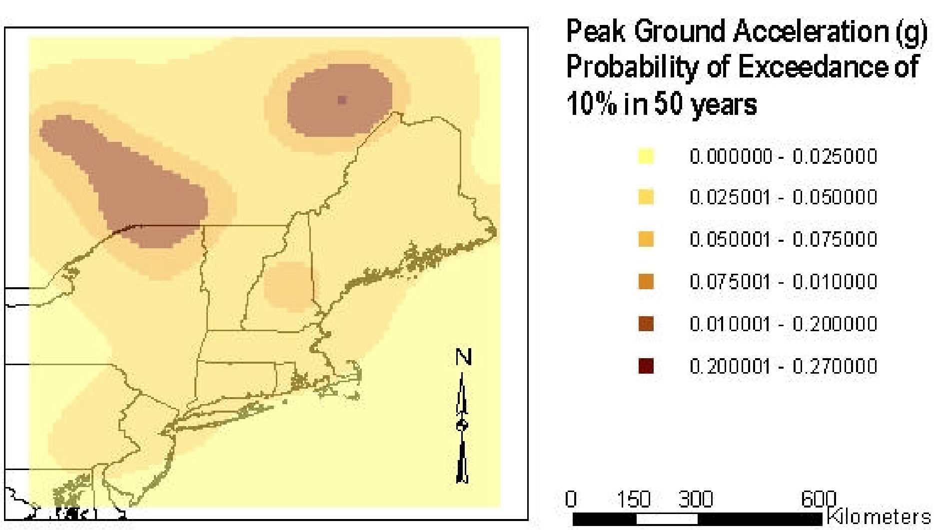
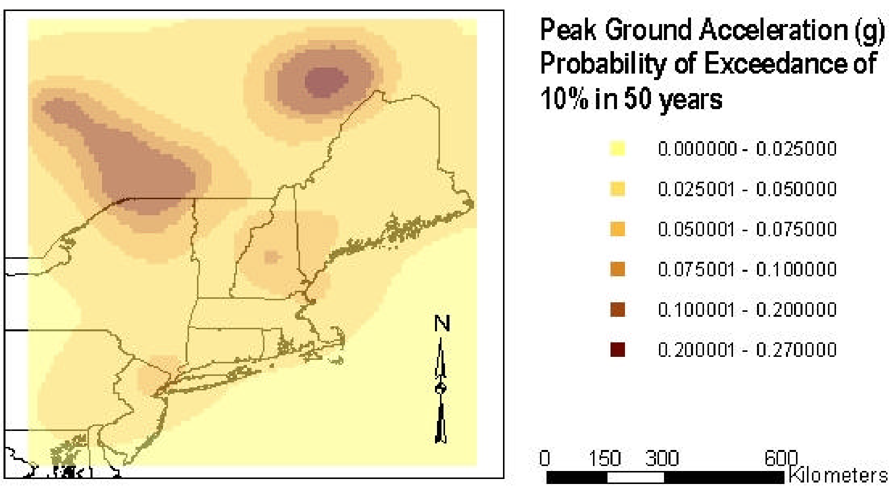


Figure IV-20. Total Seismic Hazard. Historic Seismicity Including 17th Century



The total hazard maps incorporating the modified Model 3 without SRAFs and with SRAFs are shown in Figure IV-20 and IV-21, respectively. Figure IV-20 can be compared to the total seismic hazard map Figure IV-11. The differences are very subtle. The New Hampshire peak is expanded in response to the addition of the 1638 event, while the two large peak areas in Quebec are slightly smaller. The use of SRAFs shows little impact on this trend when Figure IV-21 is compared with Figure IV-12. Major alterations to a catalog of a particular model will therefore affect that model significantly. The weighted averaging used in developing the total seismic hazard maps, however, has a significant homogenizing effect that makes these changes far less significant to the final maps.

Figure IV-21. Total Seismic Hazard. Adjusted Historic Seismicity, Including 17th Century



Error maps produced to compare Figures IV-20 and IV-21 to the USGS 2002 gridded PGA values are shown in Figures IV-22 and IV-23, respectively. The effect of adding the 17th century to Model 3 with unmodified seismicity was the increase of PGA in the upper Connecticut River Valley of New Hampshire and adjacent parts of Vermont and Quebec to within the “accurate” error range. When SRAFs are used, the effects are similar, but somewhat more interesting. A region of over prediction appears in central New Hampshire in response to the inclusion of the 1638 event, however areas of over prediction are eliminated near Cape Ann and New York City and the over prediction on the Quebec-New York border is reduced. Areas of "accurate" error terms and 1%g to 5%g under prediction are slightly rearranged in Quebec and Northern Maine.

Figure IV-22. Comparison of Total Hazard Maps with USGS. Historic Seismicity, Including 17th Century

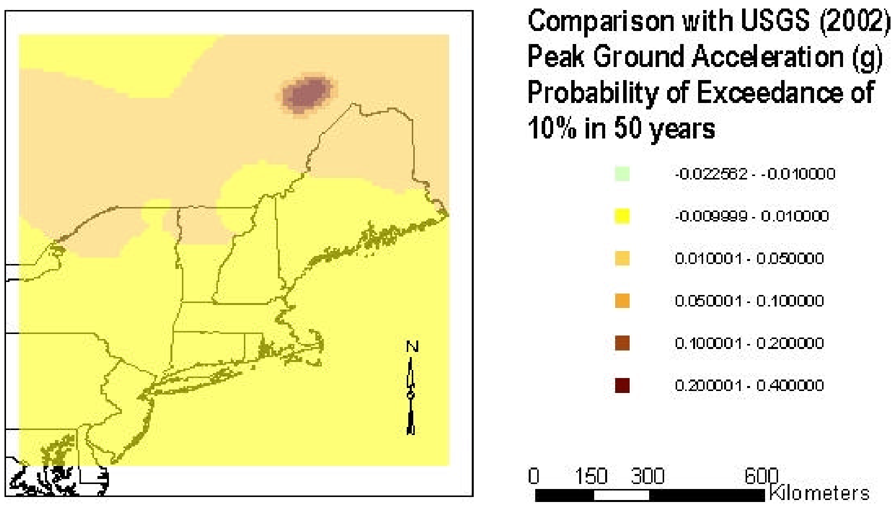
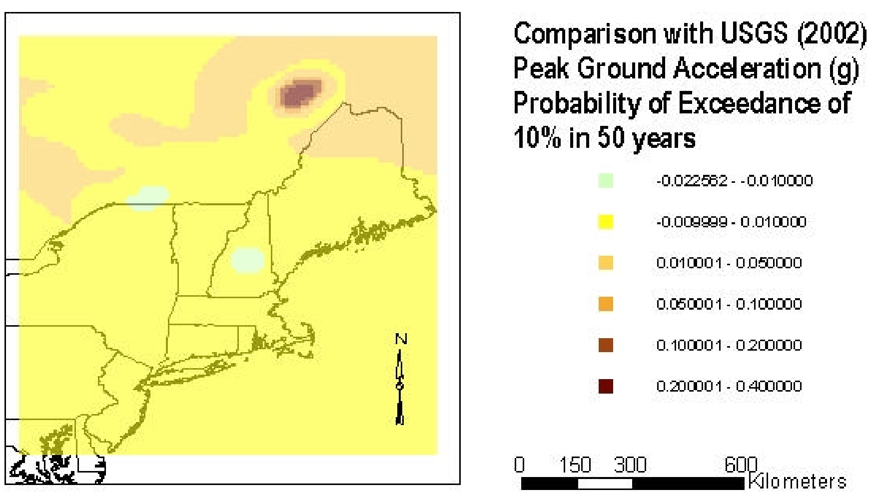


Figure IV-23. Comparison of Total Hazard Maps with USGS. Adjusted Seismicity, Including 17th Century



Having developed seismic hazard maps for New England following the procedures used in developing the USGS National Seismic Hazard Maps, with two different catalogs and two different sets of seismicity rates, and comparing the maps with editions of the USGS maps from various years, the effects of different modeling assumptions can be discussed. The effect of catalog changes, source area, ground motion models, and seismicity rates can be discussed in some detail, since maps comparing these parameters have been utilized. Less obvious effects of changes in the logic tree and the internal workings of the hazard calculation can be considered with less certainty.

The effect of the earthquake catalog used for a seismic hazard analysis was evaluated by examining the contour shapes of maps using different catalogs. Differences were found to be slight, even for significant changes to the catalog, such as the addition of 62 years of moderate to large events between 1638 and 1700. Smaller additions produced imperceptible effects. The spatial limitations of the catalog were expected to affect the seismic risk towards the edges of the source zone, necessitating a source zone enveloping significant areas beyond New England. No general trend, however, has been observed on the error maps to suggest that the selection of source zone has decreased the estimated seismic hazard estimates on the borders of the source zone for the total hazard maps. Error is higher on the northern portion of the map, however the absence of elevated error on the western side of the map suggests another cause of this difference.

The single largest modeling assumption observed in this study is the use of Seismic Rate Adjustment Factors. SRAFs of 1.27, 1.15 and 1.58 were applied to the spatially smoothed historic seismicity of Model 1, Model 2 and Model 3, respectively. The application of SRAF's brought the maps from this study in to closer agreement with the 2002 USGS data in areas of slight under prediction and even added small areas of over predicted PGA. Much of the significant differences between the New England and USGS maps appear to be related to the use of SRAFs. The SRAFs used in this study were those of Mueller, et al (1997) for the east coast United States. The source area for the New England maps, however, included areas north of the St. Lawrence River, where Mueller, et al defined factors of 1.35, 1.41, and 1.94 and Charlevoix, where factors of 1.80, 1.80, and 1.36 were provided for Model 1, Model 2 and Model 3 and a lower b value of 0.76 used. Using the smaller east coast factors result in a serious underestimation of PGA. This would appear to be the cause of most of the error in the northern portions of the map.

Figure IV-24. Model 1 Seismicity

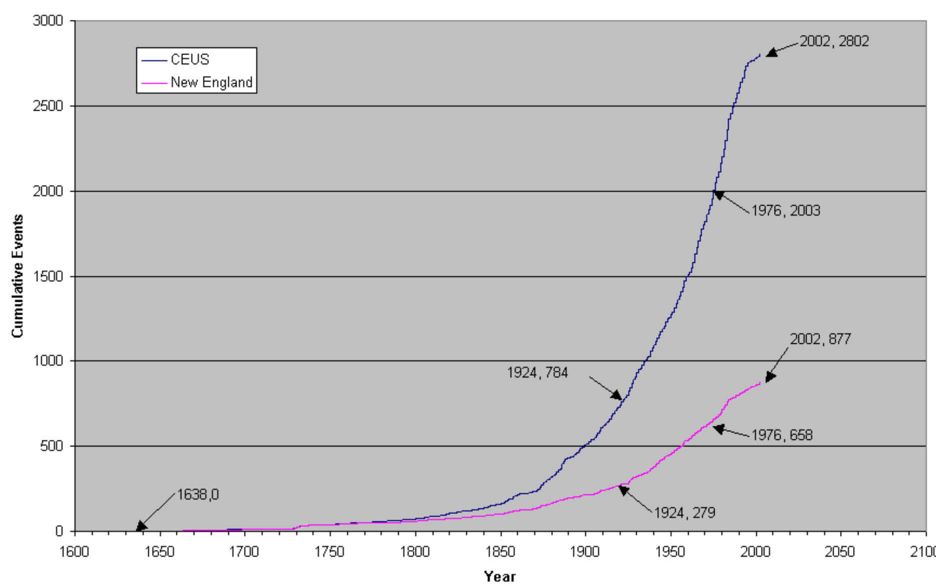
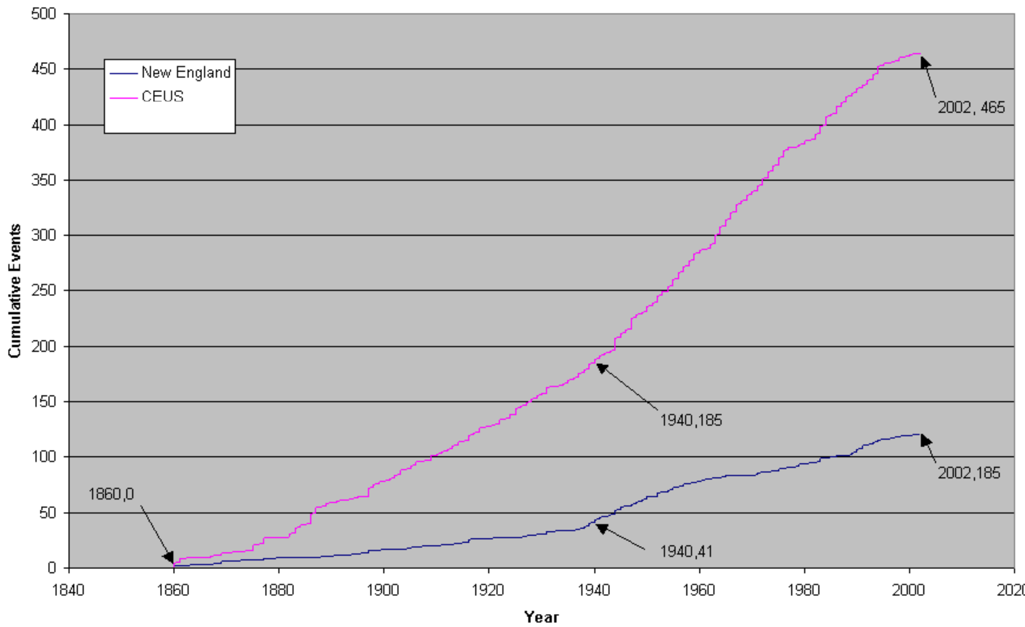
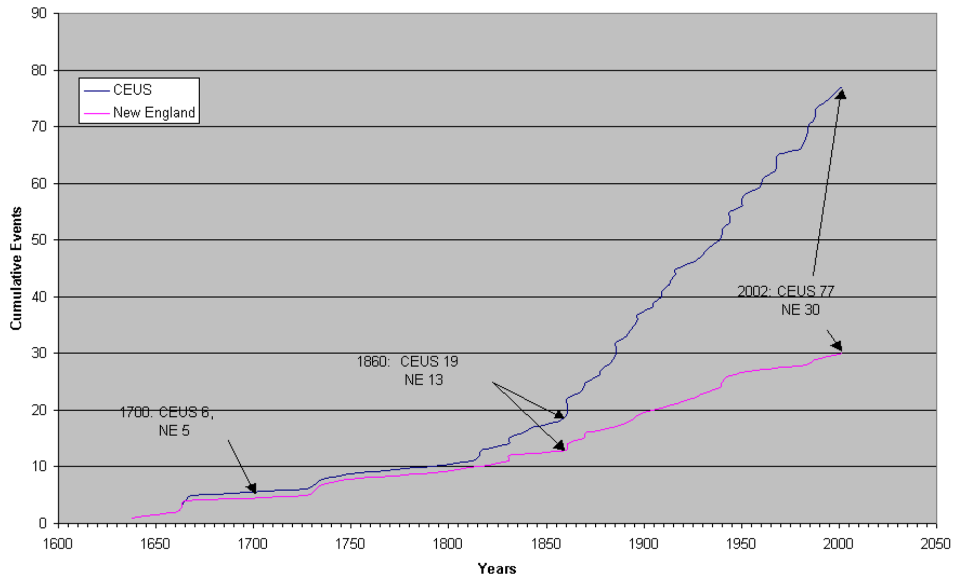


Figure IV-25. Model 2 Seismicity



Seismic rate adjustment factors are determined by calculating the ratio of the cumulative rate of events for a period of time that is considered complete and the observed rate for the model. To determine the applicability of the SRAFs used for the hazard calculations in this study, SRAFs can be determined from plots of the cumulative events versus time. The cumulative events versus time are plotted for reference magnitudes of 3.0, 4.0 and 5.0 in Figures IV-24, IV-25 and IV-26, respectively. The slopes of these curves represent the seismicity rates for events used in Model 1, Model 2 and Model 3. Cumulative seismicity rates were then calculated for events reference magnitudes of 3.0, 4.0 and 5.0 for the CEUS and New England catalogs used for this study. The recurrence laws assume that events occur at the same rate in the past, present and future. The SRAF repair nonlinearity in the cumulative rate curve by defining a new slope based on the number of events observed during the model period.

Figure IV-26. Model 3 Seismicity



The necessity of the SRAFs is indicated by changes in slope of the cumulative seismicity rate. Model 1 considers events between 1924 and the present, and is considered complete after 1976, when extensive instrumentation was completed. The CEUS curve is not exactly linear, but does not seem to significantly change slope at 1976. The break appears earlier by perhaps by 20 years. The SRAF for this data calculated according to Mueller, et al is 1.16. It should be noted that the slope of this catalog decreases in the last 10 years of the catalog because it only includes northeast events. The same procedure on the New England data finds a SRAF of 1.07. Repeating this for the Model 2 data calculates SRAFs of 1.37 for CEUS and 1.77 for New England. For Model 3, the SRAFs for CEUS is 1.59 and for New England, 1.20. The calculated SRAFs for neither the CEUS, nor New England match those used in this study, with the exception of the CEUS SRAF for Model 3. If the extended catalog since 1638 of this study is used for Model 3, the SRAFs are 1.92

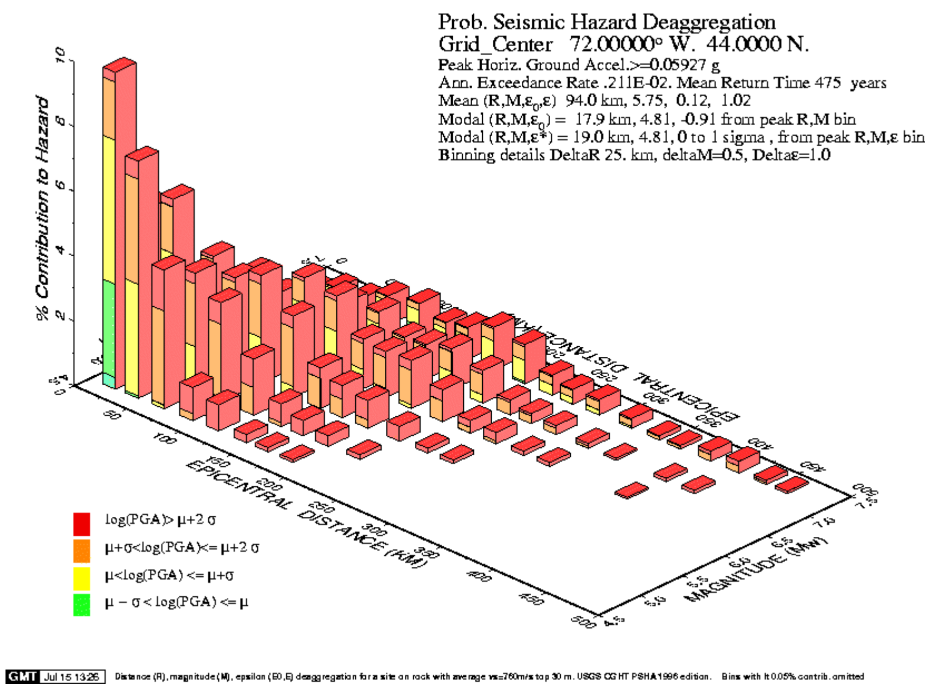
and 1.45 for CEUS and New England, respectively. This may appear to show a greater "incompleteness" of this catalog, however Figure IV-26 suggests that these higher numbers are more reflective of the longer supposed incomplete period since 1638. No effort was made to use SRAFs for the extended catalog because the catalogs used by Mueller et al in developing SRAFs for the eastern seaboard were unavailable.

The CEUS SRAFs do not match those for the east coast because Canadian and Midwest events with generally greater catalog uncertainties have been included in calculating the cumulative rates. Similarly the SRAFs for New England do not agree with Mueller, et al because events in Quebec, particularly Charlevoix have been considered. This exercise demonstrates the difficulty in adjusting historic seismicity for generating these maps. The decision of how to spatially patition the catalog area into source zones significantly affects the SRAF calculated.

The New England catalog is sufficiently complete since 1924 to consider not using a SRAF. Therefore, the Model 1 map using a SRAF of 1.27 over estimates seismicity and therefore, PGA. For Model 3, the data suggests that a smaller factor of 1.2 could be used for New England, although values near 1.6 are consistent with data over a larger area. Model 2 appears to be significantly underestimated in this study, regardless of which set of data is used to calculate the SRAF. The New England SRAF of 1.77 suggests the significant catalog uncertainty for events north of the St Lawrence reflected by the SRAFs for northern Quebec and Charlevoix from Mueller, et al.

The selection of the source area is a significant potential source of under prediction at the edges of the source area. If clusters of events beyond the source area presented a hazard to cells within the source area, then the hazard for those cells would logically be underpredicted. It is therefore important to understand how far from the edge of the source area a cell must be in order to be considered accurate. This distance can be estimated by examining a deaggregation of seismic hazard. Figure IV-27 is a deaggregation of the cell at -72° longitude and 44° latitude plotted by one of the utilities on the USGS website using 1996 national seismic hazard data (USGS, 1996b). Between Warren and Piermont, New Hampshire, this cell is the center of the source area for this study.

Figure IV-27. Deaggregation of Center of Source Area. USGS (1996b)



The contribution to the total hazard is plotted for combination of magnitude and site-to-source distance. Most of the aggregate hazard contributions are aligned along a line between small magnitude events near the site and large events at a greater distance from the site. This orientation is intuitive and would be expected at any site. Scatter of hazard contribution with respect to magnitude and distance is evident of the variation of hazard spatially. A cell at some great distance may be sufficiently active that it poses a higher risk than a closer cell for the same sized event. For magnitude 4.5 events, the hazard contributions quickly become negligible at 100km. Most of the contributions by events larger than magnitude 6.0 are less than 1% of the total. No significant contribution from any magnitude event appears at distances greater than 200km. If this cell is representative, then any cell must be at least 100km to 200 km from the edge of the source area to be accurate.

Based on the deaggregation , a region of under prediction relative to the USGS map would be expected along the perimeter of the source area The plots of the difference between the USGS map and the New England maps from this study do not reveal such a trend. One possible explanation is that when the counts were smoothed, the raw count for an individual cell could not be distributed among cells beyond the source area. This would increase the smoothed count in the other cells within the correlation distance and result in a region of artificially increased hazard around the perimeter which might mitigate the under estimation from neglecting hazard contributions beyond the source area. This would be expected to distort contours of a plot of smoothed counts. Figure III-4 does not show this sort of distortion for Model 1.

It would appear, therefore, that the size of the source area is unimportant so long as it is located correctly. The source area must include an area that is likely to contribute significantly to the hazard, but need not include areas of low hazard.

Figure III-3 shows the raw counts for Model 1. There is no evidence of a cluster of events being cut by the source area boundary. The cell counts along the perimeter are almost all either one or zero. As a result the smoothed counts are not distorted and most of the perimeter of the map appears to be with 1%g of the USGS (2002) values. The only areas of the map affected by the selection of source area are therefore those for which a cluster of increased hazard beyond the source area contributes significantly. For example, the decreased PGA in northern Maine relative to the USGS (2002) map may be related to the exclusion of events near Miramichi, New Brunswick, although this is not specifically indicated on any specific model. The exclusion of a cluster near Buffalo, New York was observed to result in an under prediction over a small area of Model 3, although this did not appear on the averaged maps.

The choice of ground motion estimators is not expected to be a significant source of error between the New England maps and the 2002 USGS maps because the same attenuation relations were used. The change of attenuation relations between the 1995 and 1996 maps appears to have significantly reduced the over prediction of low to moderate PGA values by Atkinson and Boore. The use of the revised Toro et al relation and Campbell's hybrid empirical model, along with Atkinson and Boore in 2002, however, seems to have resulted in modest PGA reductions.

It would be expected that Frankel (1995) and Frankel, et al (1996) would have used a consistent estimate of uncertainty for each map edition. Frankel, et al used a lognormal standard deviation of 0.75 for the attenuation relations used for the 1996 map. Part of the revisions made by Toro, et al (1997) was a more robust estimate of uncertainty. It was not clear what Frankel (1995) or Frankel, et al (2002) used for standard deviations, requiring assumptions to be made for this study. The assumption was made to keep the constant estimate for the attenuation relations used in 1996 and use uncertainty estimates for the other relations from the primary sources.

The standard deviation used for the Atkinson and Boore relation turned out to be smaller than the 0.75 used for the Frankel, et al and Toro, et al relations when converted to a logarithm. The Atkinson and Boore relation is known to significantly over predict PGA for low values of magnitude and distance. Therefore, the use of a lower standard deviation makes little sense, statistically. By reducing the presumed scatter in the attenuation relation, the ground motion associated with the required exceedance probability is reduced. Therefore, the use of a smaller standard deviation for the Atkinson and Boore relation may have mitigated the over prediction of the relation for the magnitude of PGA expected for the maps.

The standard deviation for the Campbell hybrid-empirical attenuation decreases with magnitude from near 0.75 at magnitudes over 7.0. Although the Campbell relation is untested, the uncertainty estimate is logical because the relation should be more accurate for smaller values due to the inclusion of empirical data. Lack of confidence in the new ground motion estimate results appropriately in a lower weight.

A significant amount of the difference between the maps in this study and in other publications may result from choice of standard deviation, but no evidence specifically suggests this. This sort of error would be expected to be more random than the inaccuracy of an attenuation relation over a small range of PGA or the adjustment of seismicity rates and would be difficult to identify.

The remaining sources of error remain buried in the procedure and the VBA subroutines, where detailed definition was required in the absence of published guidance. An example of assumptions made in developing the process is the use of magnitude and distance bins. The range of distances and magnitudes used to develop exceedance rates were consistent with the USGS maps, however, it is unknown how well the distance bins used by Frankel, et al (2002) or this study approximated the integral form of the exceedance rate. The magnitudes and distances for which tabular values exist for the Frankel, et al (1996) attenuation relation suggested that a more refined approximation might have been used for the USGS maps. Depending on the shape of the surface defined by the exceedance rate equation, the rates may have been overestimated or underestimated which would have the inverse effect on the PGA for the given probabilistic criteria. It appears likely that this sort of error is responsible for some of the small, unexplained differences between the sets of maps.

V. CONCLUSIONS & EXTENSIONS

The two primary objectives of this study were to determine if the seismic hazard calculations performed according to the USGS/NEHRP National Seismic Hazard Maps of Frankel, et al (2002) and others adequately represents New England earthquakes and if altering modeling assumptions would produce large differences in the results. The national maps are based largely on historic seismicity. It is assumed that future earthquakes will generally occur where earthquakes have occurred in the past. Therefore, seismic hazard maps were developed for New England and surrounding areas, and two parameters involving the historic seismicity, the catalog period and seismicity rates adjustments, were varied and their effects noted. Comparing these maps with the national seismic hazard maps published in 1995, 1996 and 2002 identified the effect of source area, attenuation relations and the approximation of the rate of exceedance.

The first of the two main variables, catalog period, was found to have a subtler than expected effect. Short-term catalog changes of five to ten years produced little to no effect on map contour shapes. Longer-term changes, such as the addition of events from the 17th century to Model 3 produced noticeable effects on the model that was changed, but these changes were generally homogenized when the total hazard maps were assembled. Small catalog changes produced visible changes only where isolated large events occurred, such as the 1638 event in central New Hampshire.

A greater impact was seen in the use of seismic rate adjustment factors. Mueller, et al (1997) applied factors between 1.0 and 2.0 to cell counts within the source area for this study. The use of factors developed for the United States eastern seaboard for events north of the St. Lawrence River, where Mueller, et al used higher factors, resulted in different cell counts and therefore recurrence rates. Neglecting seismic rate adjustment lowered all cell counts, however, effects were primarily visible in Quebec and Maine, within 100km to 200km of the St. Lawrence. It was also shown that choice of source zone greatly affects the magnitude of SRAFs and that the east coast factors used in this study were generally not supported by either total CEUS data or data within the source area of this study. To match the observed seismicity rate of the New England source area, no SRAF would likely be used for Model 1, while a larger one would be used for Model 2 and a smaller one would be used for Model 3. Errors of up to 5%g were attributed to the selection of SRAFs. Selection of b value for the recurrence law proved to be even more critical as shown by the high error in Charlevoix, but this is more localized and did not seem to affect New England hazard estimates.

Other error, such as the effect of the source area boundaries, the coarseness of rate of exceedance estimate descritization, and the assembly of the total hazard maps based on PGA rather than seismicity rates, were found to result in errors of ±1%g. Although this error is significant in terms of percent error, it is insignificant to engineering applications. Therefore minor errors due to assumptions that were required to complete the published procedure did not result in significant errors.

The mapping procedure appears relatively insensitive to changes in modeling assumptions, such as catalog, SRAFs and even attenuation relations. This is most likely due to the combination of multiple models with varying catalog periods and reference magnitudes for estimating recurrence and multiple ground motion relations.

This is evident by the modest contour shape changes between the 1995 and 1996 maps when Model 2 was added. Although Model 2 is somewhat different from the other models, it is sufficiently similar that when diluted by a weighting factor, the only explicitly visible contour features are those that are very different from the other models. The effects of large changes, such as the addition of Model 2 to the 1996 maps and adding the 1638 New Hampshire earthquake to Model 3 manifest as subtle contour changes on the averaged maps.

The changes made by this study were intended to be major changes that would better represent New England earthquakes, yet the effect of changing the Model 3 catalog and eliminating SRAFs were not as prominent as expected. Therefore, the Frankel, et al procedure and the assumptions within seem reasonable because changes produce practically insignificant error or refinement. The only changes that produced significant differences between this study and the USGS maps was the use of the wrong b value around Charlevoix (which was not even in the area of interest to this study) and the use of East Coast SRAFs near the St. Lawrence valley where Mueller, et al defined higher values. The national seismic hazard maps should therefore be adequate for most engineering applications for which correct maps are available.

Due to the resilience of the hazard calculation procedure, minor changes in the procedure, such as the assumptions made due to incomplete procedures, did not produce significant results. Therefore, this procedure lends itself to customization to further refine the maps to account for region-specific or project specific requirements, although the refinement may be subtle. For example, a smaller source area could have been selected for a site-specific analysis. Although some judgment would be required in developing the source area to avoid excluding events that would affect the site, this study shows that such an analysis is possible. A user of the national maps assumes that the probabilistic criteria for which the maps are developed are appropriate for their work. With this procedure, any rate of exceedance could have been selected to reflect the risk tolerance and design life of any project. By substituting attenuation relations, spectral acceleration, peak velocity or intensity could be mapped.

Although it was not explicitly tested in this study, there is uncertainty regarding earthquake causative mechanisms in New England, particularly for large events. It is unclear whether current active seismicity reflects zones of ancient weakness or aftershock sequences from events caused by static fatigue. This demonstrates the importance of the background seismicity model. In this study, Model 4 was modified to use a higher reference magnitude to avoid underestimating the effect of large events and the difficulties associated with using SRAFs (although there is no suggestion that Frankel, et al (1996) used SRAFs for Model 4). Modifications to assess this issue could have been more drastic, such as the addition of an additional background model with a reference magnitude of perhaps m_{bLg} 6.0 and a longer catalog period. Combining this model with the others using this procedure would have been a straightforward spreadsheet problem once the grid values were calculated. Some change in the final maps would have been observed, but they would probably not have been overwhelming.

Many of the seismic parameters that were encountered in this study warrant future investigation. A recurring theme in this study is the importance of a quality earthquake catalog. Further study of historic earthquakes may help fill out the catalog such that SRAFs are not necessary or may reveal more large events in the past that should be considered when calculating seismic hazard. It was found in this study that adding events to the catalog for one of the models did not dramatically alter the final maps. The removal of events prior to the complete catalog period could also be investigated. If the data from incomplete periods is not absolutely necessary to determine the map contours, then maps made without it will be more rational if not more accurate.

The recurrence model used for the hazard calculation was questioned in this study in a few different ways. The first issue involves the causative mechanisms for New England earthquakes. It is not known whether current seismicity represents areas of ancient weakness that can be expected to be the source of future earthquakes of all sizes or if the seismicity represents aftershock sequences from large events of unexplained cause. This issue relates to concerns regarding the applicability of the Gutenberg-Richter recurrence law to interplate earthquakes. The analysis of Model 4 in this study revealed the fact that Gutenberg-Richter recurrence model developed using different reference magnitudes had different intercepts (a values). Therefore, either the linear model is inappropriate or the slope (b value) provided by Frankel, et al (1996) incorrect. The use of the wrong b value for Charlevoix contributed to very large under-prediction of PGA. Understanding of the cause and prediction of New England earthquakes is not yet adequate.

The calculation of seismic hazard is inherently uncertain. Although probabilistic analysis facilitates rational decision-making, it is entirely dependent on the quality of the uncertainty estimate. A mathematical model, like the attenuation relations, which is defined in terms of a mean and standard deviation, may be easily used to determine the probability of a particular outcome or the value associated with a specified probability so long as a probability distribution is known. The uncertainty estimate is rational and based on the data. The seismic hazard calculation is made up of mathematical models and a logic tree. Uncertainty in a logic tree is not entirely rational. It is expressed in terms of the relative likelihood of competing branches, rather than the fit of any single model to data. Uncertainty in this analysis, although quantified is not completely rational.

Since the measure of uncertainty is integral to the quality of a probabilistic seismic hazard analysis, a more robust quantification of uncertainty would be useful. In this study the primary measure of uncertainty was the standard deviation of the attenuation relation. Values were assumed for each relation without any knowledge as to how well they would quantify the uncertainty of the total analysis. As a result the uncertainty in the magnitude conversion, recurrence model and a few smaller parameters was not quantified. Selecting different standard deviations than Frankel, et al may have resulted in errors of the order of a few %g. A useful topic of future study would be an accounting of all uncertainty in the hazard calculation, which could result in small refinement of the hazard data.

The seismic hazard calculation procedure described herein and by Frankel, et al (2002) for development of seismic hazard maps used by the NEHRP *Provisions* is sufficiently versatile and general that it can be used for regional or national applications with little modification. The calculation procedure is resistant to large changes caused by changing modeling assumptions by utilizing an extensive logic tree and spatial smoothing. It can also be customized with low risk of unrealistic values because it is relatively insensitive to changes in modeling parameters. This allows the maps to evolve and incorporate new models, like the Campbell attenuation relation, as they are available without inflicting drastic changes on the final maps. This aids designers by providing some consistency in seismic loading standards between editions of design codes and does not require new maps to be implemented prematurely.

The national seismic hazard maps will evolve, as they have since 1976, as seismologists and engineers better understand the mechanics of earthquakes both at the edges and interiors of tectonic plates. One can hope that the calculation procedure continues to incorporate an extensive, but practical set of models to predict ground motion parameters. A large number of models, as shown in this study, prevents bias and decreases the sensitivity to small and large modeling assumptions. Too many models, however, will increase the computational power required to perform this type of analysis and would prohibit the type of custom hazard calculation that this study represents. The current map balances these needs very well. Future maps should attempt to maintain this balance.

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VII. APPENDICES

Appendix A: Gaussian Spatial Smoothing Subroutine

```
Option Explicit
 Type cell
     lat As Single
     long As Single
     count As Single
     End Type

   Option Base 1


Sub Smoothing()

   Dim grid(100, 100) As cell
   Dim c As Double, D As Double
   Dim N(100, 100) As Double, num As Double, denom As Double
   Dim i As Integer, j As Integer, k As Integer, l As Integer
   Const pi = 3.14159265358979

   'Initialize by selecting longitude (first column) of first cell (first row).
   For i = 1 To 100
      For j = 1 To 100
         grid(i, j).long = ActiveCell.Value
         ActiveCell.Offset(0, 1).Select
         grid(i, j).lat = ActiveCell.Value
         ActiveCell.Offset(0, 1).Select
         grid(i, j).count = ActiveCell.Value
         ActiveCell.Offset(1, -2).Select
      Next j
   Next i

   c = InputBox("Please Enter Gaussian Correlation Distance in km", "Correlation Distance", 0)

   Sheets("smoothed").Select
   Range("a4").Select

   For i = 1 To 100
      For j = 1 To 100
         num = 0
         denom = 0
         For k = 1 To 100
            For l = 1 To 100
               D = Distance(grid(i, j).long * pi / 180, grid(i, j).lat * pi / 180, grid(k, l).long * pi / 180,
grid(k, l).lat * pi / 180)
```

```
                If D <= c Then
                    'Gaussian Smoothing Function (Frankel 1995)
                    num = num + grid(k, l).count * Exp(-D ^ 2 / c ^ 2)
                    denom = denom + Exp(-D ^ 2 / c ^ 2)
                End If
            Next l
        Next k
        If denom = 0 Then  ' Check against division be zero
            denom = 1
        End If
        N(i, j) = num / denom

        ActiveCell.Value = grid(i, j).long
        ActiveCell.Offset(0, 1).Select
        ActiveCell.Value = grid(i, j).lat
        ActiveCell.Offset(0, 1).Select
        ActiveCell.Value = N(i, j)
        ActiveCell.Offset(1, -2).Select
    Next j
Next i

End Sub

Function Distance(lon1, lat1, lon2, lat2)
Dim del As Double
    del = Sin(lat1) * Sin(lat2) + Cos(lat1) * Cos(lat2) * Cos(lon2 - lon1)
    If del < 1 Then
        Distance = 6378 * Application.WorksheetFunction.Acos(del)
    Else
        Distance = 0
    End If
    'Distance = 6378 * Application.WorksheetFunction.Acos(Sin(lat1) * Sin(lat2) + Cos(lat1) *
Cos(lat2) * Cos(lon2 - lon1))

End Function
```

Appendix B: Seismic Hazard Calculation Subroutine-Historic Seismicity (Models 1, 2 & 3)

```
Option Explicit
 Type cell  'Record of latitude, longitude and smoothed N of every square on 0.1deg x 0.1 deg grid
       lat As Single
       long As Single
       count As Single
       End Type
 Dim T As Integer, Mref As Integer

 Option Base 1
 Dim grid(100, 100) As cell


Sub PGA() ' Finds PGA w/ 10% PE in 50 years according to procedures in Frankel 2002 and
references

    Dim i As Integer, j As Integer, p As Integer
    Dim u As Double

   Sheets("smoothed").Select
   Range("a4").Select
   i = 1
   j = 1
    For i = 1 To 100
       For j = 1 To 100
          grid(i, j).long = ActiveCell.Value
          ActiveCell.Offset(0, 1).Select
          grid(i, j).lat = ActiveCell.Value
          ActiveCell.Offset(0, 1).Select
          grid(i, j).count = ActiveCell.Value
          ActiveCell.Offset(1, -2).Select
       Next j
    Next i

   Sheets("PGA").Select
   Range("a4").Select
   T = InputBox("Please Enter Catalog Time period in years", 1)
   Mref = InputBox("Please Enter Reference Magnitude (mbLg)", 1)

   'For i = 51 To 60     'Test range NH Lakes Region
    ' For j = 51 To 60

    For i = 1 To 100
      For j = 1 To 100
```

```
        u = Check(0, 1, grid(i, j).long, grid(i, j).lat)
        p = Data(grid(i, j).long, grid(i, j).lat, u)
     Next j
   Next i

End Sub

Function Check(u, i, lon, lat)  'This works!!
   Dim j As Integer
   Dim error As Double
   Const Rate0 = 0.0021072103 'Annual Rate of Exceedance with PE of 10% in 50yrs
     Const e0 = 0.000001     'error threshold for rate
      error = 1
   For j = 1 To 10
      error = Rate0 - Rate(u + i * j, lon, lat)
      If u + i < 0.00001 Then
         Check = u
         Exit For
      ElseIf Abs(error) < e0 Then
         Check = u + i * j
         Exit For
      ElseIf error > 0 Then
         Check = Check(u + i * (j - 1), i / 10, lon, lat) ' Returns to Original and Checks smaller
interval
         Exit For
      End If
      Next j

End Function


Function Rate(u, lon, lat)      'Works with correct dummy rate
Const pi = 3.14159265358979
Dim D As Double, N(51) As Double ' Binned count for 10km bis + test variable
Dim b As Single, rate1 As Double
Dim Dk As Double, Ml As Integer
Dim i As Integer, j As Integer, k As Integer, l As Integer


For i = 1 To 100      ' Bin counts by distance   '
   For j = 1 To 100
      If grid(i, j).long = lon Then
         D = (grid(i, j).lat - lat) * 111.3
            Else
      D = Distance(lon * pi / 180, lat * pi / 180, grid(i, j).long * pi / 180, grid(i, j).lat * pi / 180)
      End If
```

```
        For k = 1 To 50  ' Distance bins of <10km to > 500km
            If Abs(D) < k * 10 Then
                N(k) = N(k) + Abs(grid(i, j).count)
                Exit For
            End If
        Next k
    Next j
Next i

' Determine b for Charlevoix, Quebec
'If lat/long area Then
'   b = 0.76
'Else
    b = 0.95
'EndIf

'rate1 = 0.0024  / (u + 1)  'u = 0.139
'Dk = 41
'k = 51
'l = 5

rate1 = 0
For k = 1 To 50    ' Distance bins of <10km to > 500km
    For l = 5 To 7  'Maxnitude bins of mbLg intervals of 4.5 to 5.5, 5.5 to 6.5, 6.5 to 7.5 represnted
by ave.
        'Rate of exceedance for ground motion parameter for cell after Frankel 1995
        '= sum over distance and magnitude bins of product of temporal and ground motion
probabilities
        Dk = k * 10 - 5
        Ml = l
            If N(k) > 0 Then
                rate1 = rate1 + 10 ^ (Log10(N(k) / T) - b * (Ml - Mref)) * PPGA(u, Dk, Ml)
            'ActiveCell.Value = u
            'ActiveCell.Offset(0, 1).Select
            'ActiveCell.Value = rate1
            'ActiveCell.Offset(1, -1).Select
            'MsgBox ("rate = " & rate1)
            End If
    Next l
Next k
Rate = rate1

End Function
```

```
Function PPGA(u, D, mbLg) 'Detrmines PE for gound motion based on weighted average of four models

Dim M As Single
Const wT = 0.286    'Toro, et al 1997
Const wF = 0.286    'Frankel, et al 1996
Const wAB = 0.286   'Atkinson & Boore 1995
Const wC = 0.143    'Campbell 2002/2003
Dim MBA As Single, MJ As Single
' Need magnitude conversion as necessary.  This appears to work
MBA = 2.715 - 0.277 * mbLg + 0.127 * mbLg ^ 2 'Boore and Atkinson 1987
MJ = 2 / 3 * (17.76 + 0.36 * mbLg + 0.14 * mbLg ^ 2) - 10.7 'Johnson 1996, Figure 7
M = 0.5 * MBA + 0.5 * MJ

PPGA = wT * Toro(u, D, mbLg) + wF * Frankel(u, D, mbLg) + wAB * A_B(u, D, M) + wC * Campbell(u, D, M)

End Function


Function NatLog(x)
'Aparently VBA uses Log to mean natural Log
Dim y As Double

y = x * 1#
NatLog = Log(y)
End Function


Function Log10(x)
Log10 = Log(x) / Log(10#)
End Function


Function Toro(u, D, M)  'Finds Z Transform for Toro, et al 1997 Attenuation Relationship mbLg
'ln PGA in %g as a function of mbLg, Rm for 5< m < 8, 1km < R < 500km Median Midcontinent Coef.
Dim lnmean As Double, stdev As Double
Dim Rm As Single
Dim sm As Double, sd As Double 'Error terms for model and depth mbLg

Rm = (D ^ 2 + 9.3 ^ 2) ^ 0.5 ' Joyner-Boore Epicentral Distance to hypocentral distnace km
'BC Site condition Conversion multiply u by 1.52
lnmean = (2.07 + 1.2 * (M - 6) - 0 * (M - 6) ^ 2 - 1.28 * NatLog(Rm) - (1.23 - 1.28) * Application.WorksheetFunction.Max(NatLog(Rm / 100), 0) - 0.0018 * Rm)
```

```
stdev = 0.75 'ln sigma constant according to Frankel 1996???
Toro = 1 - Application.WorksheetFunction.LogNormDist(u / 1.52, lnmean, stdev)
End Function


Function Frankel(u, D, M)  'Finds Z Transform for Frankel, et al 1996 Attenuation Relationship
'log PGA in %g as a function of M, R for 4.4 < m < 8.2, 10km < R < 1000km
'tabular data converted to interpolated curves for mbLg magnitudes used in magnitude bins
Dim lnmean As Double, stdev As Double
Dim x As Double
x = Log10(D)
If M = 5 Then
   lnmean = NatLog(10 ^ (-0.3813 * x ^ 3 + 1.895 * x ^ 2 - 4.4841 * x + 2.3954))
   ElseIf M = 6 Then
   lnmean = NatLog(10 ^ (-0.2969 * x ^ 3 + 1.4789 * x ^ 2 - 3.686 * x + 2.3964))
   ElseIf M = 7 Then
   lnmean = NatLog(10 ^ (-0.2829 * x ^ 3 + 1.4522 * x ^ 2 - 3.5766 * x + 2.7514))
   Else
   lnmean = NatLog(10 ^ (0.5))
End If

stdev = 0.75 'constant according to Frankel 1996???
Frankel = 1 - Application.WorksheetFunction.LogNormDist(u, lnmean, stdev)
End Function


Function A_B(u, D, M)  'Finds Z Transform for Atkinson & Boore 1995 Attenuation Relationship
'log PGA in cm/s^2 as a function of M, R for 4< m < 7.25, 10km < R < 500km
Dim lnmean As Double, stdev As Double
'BC Site condition Conversion multiply by 1.52
lnmean = NatLog(10 ^ (3.79 + 0.298 * (M - 6) - 0.0536 * (M - 6) ^ 2 - Log10(D) - 0.00135 * D))
stdev = NatLog(10 ^ 0.25) '= ln sigma constant
A_B = 1 - Application.WorksheetFunction.LogNormDist(981 * u / 1.52, lnmean, stdev)
End Function


Function Campbell(u, D, M) 'Finds Z Transform for Campbel 2003 Attenuation Relationship
'ln PGA in %g as a function of M, R for 5< m < 8.2, 0km < R < 1000km
Dim lnmean As Double, stdev As Double
Dim R As Single, f3 As Double, sa As Single, se As Single
R = (D ^ 2 + (0.683 * Exp(0.416 * M)) ^ 2) ^ 0.5
If R <= 70 Then
   f3 = 0
   ElseIf R > 130 Then
   f3 = 0.683 * NatLog(R / 70) + 0.416 * NatLog(R / 130)
   Else
```

```
    f3 = 0.683 * NatLog(R / 70)
End If
'BC Site condition Conversion multiply by 1.52
lnmean = (0.0305 + 0.633 * M - 0.0427 * (8.5 - M) ^ 2 - 1.591 * NatLog(R) + (-0.00428 +
0.000483 * M) * D + f3)
If M < 7.16 Then
    sa = 1.03 - 0.086 * M
    Else
    sa = 0.414
    End If
 se = 0.28 ' averaged value to avoid using fifth order polynomial
stdev = sa + se
Campbell = 1 - Application.WorksheetFunction.LogNormDist(u / 1.52, lnmean, stdev)
End Function

Function Data(lon, lat, u)

    ActiveCell.Value = lon
    ActiveCell.Offset(0, 1).Select
    ActiveCell.Value = lat
    ActiveCell.Offset(0, 1).Select
    ActiveCell.Value = u
    ActiveCell.Offset(1, -2).Select

    Data = 0
End Function

Function Distance(lon1, lat1, lon2, lat2)

Distance = 6378 * Application.WorksheetFunction.Acos(Sin(lat1) * Sin(lat2) + Cos(lat1) *
Cos(lat2) * Cos(lon2 - lon1))

End Function
```

Appendix C: Seismic Hazard Calculation Subroutine-Background Seismicity (Model 4)

```
Option Explicit
 Type cell  'Record of latitude, longitude and smoothed N of every square on 0.1deg x 0.1 deg grid
       lat As Single
       long As Single
       count As Single
       End Type
 Dim T As Integer, Mref As Integer

 Option Base 1
 Dim grid(100, 100) As cell


Sub PGA() ' Finds PGA w/ 10% PE in 50 years according to procedures in Frankel 2002 and
references

    Dim i As Integer, j As Integer, p As Integer
    Dim u As Double, u1 As Double

   Sheets("smoothed").Select
   Range("a4").Select
   i = 1
   j = 1
   For i = 1 To 100
      For j = 1 To 100
         grid(i, j).long = ActiveCell.Value
         ActiveCell.Offset(0, 1).Select
         grid(i, j).lat = ActiveCell.Value
         ActiveCell.Offset(0, 1).Select
         grid(i, j).count = ActiveCell.Value
         ActiveCell.Offset(1, -2).Select
      Next j
   Next i

   Sheets("PGA").Select
   Range("a4").Select
   T = InputBox("Please Enter Catalog Time period in years", 1)
   Mref = InputBox("Please Enter Reference Magnitude (mbLg)", 1)

   'For i = 51 To 60     'Test range NH Lakes Region
    ' For j = 51 To 60
   u = Check(0, 1, grid(41, 41).long, grid(41, 41).lat)
   u1 = Check(0, 1, grid(82, 82).long, grid(82, 82).lat)
   If u1 <> u Then
```

```
        MsgBox ("error u")
        End If

    For i = 1 To 100
      For j = 1 To 100
           'u = Check(0, 1, grid(i, j).long, grid(i, j).lat)
           p = Data(grid(i, j).long, grid(i, j).lat, u)
      Next j
    Next i

End Sub

Function Check(u, i, lon, lat)  'This works!!
    Dim j As Integer
    Dim error As Double
    Const Rate0 = 0.0021072103 'Annual Rate of Exceedance with PE of 10% in 50yrs
      Const e0 = 0.000001     'error threshold for rate
        error = 1
    For j = 1 To 10
        error = Rate0 - Rate(u + i * j, lon, lat)
        If u + i < 0.00001 Then
           Check = u
           Exit For
        ElseIf Abs(error) < e0 Then
           Check = u + i * j
           Exit For
        ElseIf error > 0 Then
           Check = Check(u + i * (j - 1), i / 10, lon, lat) ' Returns to Original and Checks smaller
interval
           Exit For
        End If
        Next j

End Function

Function Rate(u, lon, lat)      'Works with correct dummy rate
Const pi = 3.14159265358979
Dim D As Double, N(51) As Double, No As Double ' Binned count for 10km bis + test variable
Dim b As Single, rate1 As Double
Dim Dk As Double, Ml As Integer
Dim i As Integer, j As Integer, k As Integer, l As Integer

' Determine b for Charlevoix, Quebec
'If lat/long area Then
'   b = 0.76
'Else
```

```
    b = 0.95
'EndIf

'rate1 = 0.0024  / (u + 1)  'u = 0.139
'Dk = 41
'k = 51
'l = 5
No = 9 / 10000 / 88 'Magnitude 5.0+ since 1924 distributed roughly by area assuming 88sqkm/cell
rate1 = 0
For k = 1 To 50    ' Distance bins of <10km to > 500km
    For l = 5 To 7  'Maxnitude bins of mbLg intervals of 4.5 to 5.5, 5.5 to 6.5, 6.5 to 7.5 represnted
by ave.
        'Rate of exceedance for ground motion parameter for cell after Frankel 1995
        '= sum over distance and magnitude bins of product of temporal and ground motion
probabilities
        'N(k) = 8 / 10000
        Dk = k * 10 - 5
        Ml = l
        N(k) = No * pi * (200 * k - 100)
            If N(k) > 0 Then
                rate1 = rate1 + 10 ^ (Log10(N(k) / T) - b * (Ml - Mref)) * PPGA(u, Dk, Ml)
           'ActiveCell.Value = u
            'ActiveCell.Offset(0, 1).Select
           'ActiveCell.Value = rate1
            'ActiveCell.Offset(1, -1).Select
           'MsgBox ("rate = " & rate1)
           End If
    Next l
Next k
Rate = rate1

End Function

Function PPGA(u, D, mbLg) 'Detrmines PE for gound motion based on weighted average of four
models

Dim M As Single
Const wT = 0.286    'Toro, et al 1997
Const wF = 0.286    'Frankel, et al 1996
Const wAB = 0.286   'Atkinson & Boore 1995
Const wC = 0.143    'Campbell 2002/2003
Dim MBA As Single, MJ As Single
' Need magnitude conversion as necessary.  This appears to work
MBA = 2.715 - 0.277 * mbLg + 0.127 * mbLg ^ 2 'Boore and Atkinson 1987
MJ = 2 / 3 * (17.76 + 0.36 * mbLg + 0.14 * mbLg ^ 2) - 10.7 'Johnson 1996, Figure 7
M = 0.5 * MBA + 0.5 * MJ
```

```
PPGA = wT * Toro(u, D, mbLg) + wF * Frankel(u, D, mbLg) + wAB * A_B(u, D, M) + wC *
Campbell(u, D, M)

End Function


Function NatLog(x)
'Aparently VBA uses Log to mean natural Log
Dim y As Double

y = x * 1#
NatLog = Log(y)
End Function


Function Log10(x)
Log10 = Log(x) / Log(10#)
End Function


Function Toro(u, D, M)  'Finds Z Transform for Toro, et al 1997 Attenuation Relationship mbLg
'ln PGA in %g as a function of mbLg, Rm for 5< m < 8, 1km < R < 500km Median Midcontinent
Coef.
Dim lnmean As Double, stdev As Double
Dim Rm As Single
Dim sm As Double, sd As Double 'Error terms for model and depth mbLg

Rm = (D ^ 2 + 9.3 ^ 2) ^ 0.5 ' Joyner-Boore Epicentral Distance to hypocentral distnace km
'BC Site condition Conversion multiply u by 1.52
lnmean = (2.07 + 1.2 * (M - 6) - 0 * (M - 6) ^ 2 - 1.28 * NatLog(Rm) - (1.23 - 1.28) *
Application.WorksheetFunction.Max(NatLog(Rm / 100), 0) - 0.0018 * Rm)

stdev = 0.75 'ln sigma constant according to Frankel 1996???
Toro = 1 - Application.WorksheetFunction.LogNormDist(u / 1.52, lnmean, stdev)
End Function


Function Frankel(u, D, M)  'Finds Z Transform for Frankel, et al 1996 Attenuation Relationship
'log PGA in %g as a function of M, R for 4.4 < m < 8.2, 10km < R < 1000km
'tabular data converted to interpolated curves for mbLg magnitudes used in magnitude bins
Dim lnmean As Double, stdev As Double
Dim x As Double
x = Log10(D)
If M = 5 Then
   lnmean = NatLog(10 ^ (-0.3813 * x ^ 3 + 1.895 * x ^ 2 - 4.4841 * x + 2.3954))
```

```
    ElseIf M = 6 Then
    lnmean = NatLog(10 ^ (-0.2969 * x ^ 3 + 1.4789 * x ^ 2 - 3.686 * x + 2.3964))
    ElseIf M = 7 Then
    lnmean = NatLog(10 ^ (-0.2829 * x ^ 3 + 1.4522 * x ^ 2 - 3.5766 * x + 2.7514))
    Else
    lnmean = NatLog(10 ^ (0.5))
End If

stdev = 0.75 'constant according to Frankel 1996???
Frankel = 1 - Application.WorksheetFunction.LogNormDist(u, lnmean, stdev)
End Function


Function A_B(u, D, M)  'Finds Z Transform for Atkinson & Boore 1995 Attenuation Relationship
'log PGA in cm/s^2 as a function of M, R for 4< m < 7.25, 10km < R < 500km
Dim lnmean As Double, stdev As Double
'BC Site condition Conversion multiply by 1.52
lnmean = NatLog(10 ^ (3.79 + 0.298 * (M - 6) - 0.0536 * (M - 6) ^ 2 - Log10(D) - 0.00135 * D))
stdev = NatLog(10 ^ 0.25) '= ln sigma constant
A_B = 1 - Application.WorksheetFunction.LogNormDist(981 * u / 1.52, lnmean, stdev)
End Function


Function Campbell(u, D, M) 'Finds Z Transform for Campbel 2003 Attenuation Relationship
'ln PGA in %g as a function of M, R for 5< m < 8.2, 0km < R < 1000km
Dim lnmean As Double, stdev As Double
Dim R As Single, f3 As Double, sa As Single, se As Single
R = (D ^ 2 + (0.683 * Exp(0.416 * M)) ^ 2) ^ 0.5
If R <= 70 Then
    f3 = 0
    ElseIf R > 130 Then
    f3 = 0.683 * NatLog(R / 70) + 0.416 * NatLog(R / 130)
    Else
    f3 = 0.683 * NatLog(R / 70)
End If
'BC Site condition Conversion multiply by 1.52
lnmean = (0.0305 + 0.633 * M - 0.0427 * (8.5 - M) ^ 2 - 1.591 * NatLog(R) + (-0.00428 +
0.000483 * M) * D + f3)
If M < 7.16 Then
    sa = 1.03 - 0.086 * M
    Else
    sa = 0.414
    End If
 se = 0.28 ' averaged value to avoid using fifth order polynomial
stdev = sa + se
Campbell = 1 - Application.WorksheetFunction.LogNormDist(u / 1.52, lnmean, stdev)
```

```
End Function


Function Data(lon, lat, u)

    ActiveCell.Value = lon
    ActiveCell.Offset(0, 1).Select
    ActiveCell.Value = lat
    ActiveCell.Offset(0, 1).Select
    ActiveCell.Value = u
    ActiveCell.Offset(1, -2).Select

    Data = 0
End Function

Function Distance(lon1, lat1, lon2, lat2)

Distance = 6378 * Application.WorksheetFunction.Acos(Sin(lat1) * Sin(lat2) + Cos(lat1) *
Cos(lat2) * Cos(lon2 - lon1))

End Function
```