Using Custom Probabilistic Seismic Hazard Analysis Maps Based on U.S. Geological Survey National Seismic Hazard Mapping Procedures

When site conditions fail to conform to an applicable design code, or when a variance to the code is desired, a customized probabilistic seismic hazard analysis map can be of great use.

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In seismically active regions, earthquake effects are often the controlling lateral load in the design of structures. 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. Central to code-based seismic design are seismic hazard maps, which provide a ground motion parameter, usually an acceleration value, which is applied in some form as a lateral force to the structure.

Cornell introduced methods for evaluating seismic hazard probabilistically.[1] Uncertainty in the quantity, magnitude and source of earthquakes can be considered by expressing seismic risk in terms of the return period, in the same way that wind and flood effects are evaluated in civil engineering. An estimated return period for a particularly damaging natural event can be used to rationally balance the risk of economic loss from that event and the cost of mitigating that risk. This approach typically results in more economical designs than the use of a "maximum credible" event as a design criterion.

Like meteorological events, the earthquake recurrence for a given source can be estimated based on the historical record. Earthquake prediction, however, involves the uncertainty of the temporal distribution of the event magnitude, as well as spatial distribution on multiple sources. The effect on a particular site of a given earthquake at some point on a source is also uncertain. Cornell developed solutions for evaluating the seismic hazard from a source using statistics.[1] By allowing the risk from all potential earthquakes on all potential sources to contribute to the seismic hazard at a site by weighting them according to probabilities, a rational, and possibly more realistic, risk analysis could be made. This type of analysis is called probabilistic seismic hazard analysis (PSHA).

The United States Geological Survey (USGS) developed its first national seismic hazard maps in 1976 and provided peak ground acceleration with a probability of exceedance of 10 percent in fifty 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 seismic design provisions in most model building codes. Later USGS efforts included maps of peak acceleration and peak velocity, as well as design response spectra ordinates. These efforts were incorporated in subsequent editions of the NEHRP provisions, usually a few years after their development.[2]

Procedures used in developing the maps evolved between editions, with additions and refinements made after a consensus review process. The most recent procedures are described by Frankel *et al.*[3] and are based on previous studies,[4,5] with Frankel *et al.*'s 2002 maps forming the foundation of seismic design for the next several years.[3] The contiguous forty-eight states are split roughly at the Rocky Mountains and different procedures are used for the Central and Eastern United States (CEUS) and the Western United States (WUS). Earthquake causative mechanisms and wave propagation vary considerably between the active plate boundary areas of the WUS and the more stable interplate crust of the CEUS. WUS earthquakes are larger and more frequent, and they are more likely to occur on mapped geologic features than CEUS earthquakes. However, CEUS earthquakes are felt over a much larger area because the crust in that region is older and more intact. Multiple models incorporating major known faults, spatially smoothed historic seismicity and background seismicity zones are combined with multiple ground motion estimators to account for uncertainties in modeling.

The procedure used to develop the national seismic hazard maps can be adapted to form the basis for a customized PSHA. Ground motion parameters can be calculated to correspond to the probabilistic criteria that are unavailable in published maps. In addition, instead of using the generalized CEUS or WUS modeling assumptions, adjustments can be made to be more representative of a specific region. Due to the facility with which the USGS procedures can be modified, they can be used for regional- or project-specific analysis.

Procedure

National PSHA Maps. Seismic hazard maps are created by calculating the ground motion parameter with a certain rate of exceedance at discrete points across an area of interest. Figure 1 shows the logic tree for the CEUS seismic hazard calculation as it pertains to this study. Earthquakes are assumed to follow a Poisson probability distribution (in which the probability of some number of events occurring can be determined within a given time and can be determined with an assumed rate

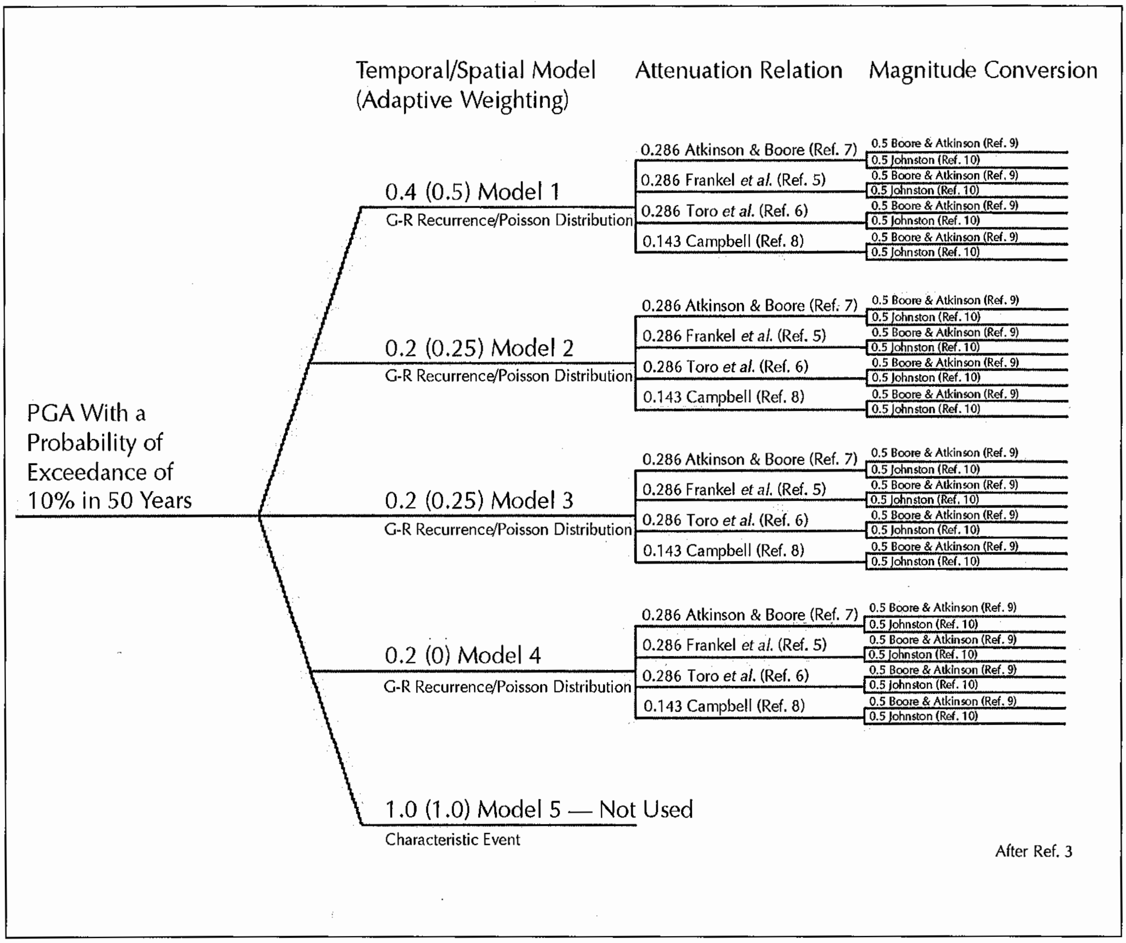

FIGURE 1. Logic tree for seismic hazard maps.

of occurrence). This distribution can be rearranged to define the probability of the exceedance of a ground motion value within a certain number of years, given an annual rate of exceedance (*i.e.*, the probability of exceedance of 10 percent in fifty years). Conversely, an annual rate of exceedance can be calculated for a specific probability of exceedance over a period of time. The peak ground acceleration (PGA) corresponding to this annual rate of exceedance can be calculated by iteration and can be plotted in order to create the seismic hazard maps.

The most recent version of the national seismic hazard maps, produced in 2002, used an earthquake catalog that included events through December 2001 to develop three historic seismicity models.[3] Model 1 consists of the smoothed, historic rate of events greater than *Lg* magnitude (m_{bLg}) 3.0 since 1924. Model 2 includes earthquakes greater than m_{bLg} 4.0 since 1860. Model 3 is based on m_{bLg} 5.0 and greater events since 1700. 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.[4] Background seismicity is considered only when the inclusion of Model 4 results in higher ground motion estimates than the historic seismicity models alone. The earlier Frankel *et al.* study superimposed a Model 5 with full weight to account for characteristic earthquakes of moment magnitude 7.0 and greater from four areas of high hazard, none of which would be expected to pose a significant risk to New England;[5] therefore, this model was ignored. The later study by Frankel *et al.* used a finite fault model for magnitudes of 6.0 and greater in calculating gridded seismicity.[3] However, this procedure only affected very low probabilities of exceedance (less than 2 percent in fifty years), was not well described and was, therefore, neglected.

To account for catalog omissions and uncertainty in earlier earthquakes, the 2002 Frankel *et al.* study adjusted the historic seismicity rate for each model to the presumed "complete" seismicity rate.[3] This adjustment was made by multiplying the gridded seismicity by a seismic rate adjustment factor (SRAF) calculated by Mueller *et al.* for various areas, equal to the presumed complete rate divided by the observed or "counted" rate.[11]

The 2002 Frankel *et al.* study used four attenuation relations to estimate ground acceleration given an earthquake magnitude and distance.[3] A fifth relation was used for Model 5 for the USGS maps. Each attenuation relation used slightly different assumptions, particularly the choice of magnitude scale and site conditions. The 2002 Frankel *et al.* study applied a weight of 0.286 to Toro *et al.*,[6] the earlier Frankel *et al.* study[5] and Atkinson and Boore,[7] while a weight of 0.143 was assigned to the Campbell attenuation relation.[8] The Campbell attenuation relation attempts to correct errors in near source ground motions predicted by CEUS attenuation relations by using scaled WUS ground motion estimates near source.[8] Near source data are more abundant for WUS earthquakes because they are more frequent and better instrumented. This approach is novel and untested; therefore, it warrants a lower weight. For the attenuation relations requiring moment magnitude (M_w) as an input parameter, conversions by Boore and Atkinson[9] and Johnston[10] were used with equal weights to convert m_{bLg} or m_b to M_w.[3]

Custom PSHA Maps. Since this type of analysis makes intensive use of spatial data as well as involved, complicated and iterative calculations, computer software was necessary to automate the custom PSHA mapping process. Hundreds of events in the catalog had to be processed and data plotted at various stages. Therefore, a geographic information system (GIS) package was selected to process input and output data from the seismic hazard analysis. GIS allows information in databases to be plotted and manipulated spatially, making it very useful in plotting earthquakes, developing the catalogs for each model, checking processes based on spatial data and plotting results. To perform all calculations, programs were developed using a variant of the BASIC programming language, which is less powerful than other programming languages, but is more convenient to learn. These programs were executed in a commonly used spreadsheet program, thereby simplifying input and output. (While the BASIC variant was available for the GIS software, its use in the spreadsheet program was better documented, and it represented a more expedient choice.)

The maps in this study were based on a grid with 0.1° longitude by 0.1° latitude cells. The grid cell value was the weighted average of four recurrence models utilizing different sources and catalogs (as shown in Figure 1). The basic algorithm used in this study for developing the seismic hazard maps was as follows:

> For each historic seismicity model, the proper events were selected from the earthquake catalog. Using GIS, the number of events falling into each grid cell was counted. The cell counts were spatially smoothed using a programming subroutine. For the background seismicity model, the count over the entire source area was divided among all cells. 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 converged upon that corresponding to 10 percent in fifty 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 a map in GIS.[12]

The most recent earthquake catalog available from the USGS website was that used for the 1996 maps.[13] Aside from a few minor modifications mentioned by the 2002 Frankel *et al.* study, the only difference between the 1996 and 2002 catalogs is the inclusion of events from 1996 to 2001. Therefore, the 1996 USGS catalog was used for this study with events added from the northeastern United States catalogs available from Boston College's Weston Observatory. This approach allowed the custom PSHA to consider earthquakes between January 1996 and April 2003.[14]

Due to the limited coverage of the Weston catalogs and the need for computational efficiency, a source area enveloping all events expected to contribute to seismic hazard in New England was defined. A large source area was desirable because seismic waves travel well in stable crust. In addition, 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 also result in errors. For convenience, a 10° longitude by 10° latitude area was used and was centered so as to include all of New England, as well as surrounding regions of Québec and New York. 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 using a computer-aided drafting program. This grid consisted of a square array of 10,000 squares. 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). The grid was imported to the GIS package in the same coordinate system and converted to a shape file that consisted 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 (in longitude and latitude) of the midpoint of the grid as an attribute of the cell. 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.

The grid defining the source area and the events selected for each historic seismicity model are shown in Figure 2. Events greater than magnitude 3.0 since 1924 were selected for Model 1. The selection was exported as a separate database file. This process was repeated for magnitude 4.0 and greater events since 1860 for Model 2 and magnitude 5.0 events since 1700 were compiled for Model 3. 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 event counts for each historic seismicity model were exported to the spreadsheet where they were manipulated by the programming modules.

A subroutine was written (after Frankel[4]) to spatially smooth the raw counts for each model. For every cell, the subroutine calculated a new value for the cell count that was 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. If the distance from one cell to another was less than or equal to the correlation distance, then the count for that nearby cell was included in calculating the smoothed count. Frankel used the following Gaussian smoothing function to calculate the count for each cell:[4]

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

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 and divided by the sum of the exponentials, where Δ_{ij} is the distance between cells i and j and where c is the correlation distance. Following the earlier Frankel *et al.* study,[5] a correlation distance of 50 kilometers was used for Model 1, while a correlation distance of 75 kilometers was used for Models 2 and 3. This count was printed along with the cell's longitude and latitude on a new worksheet

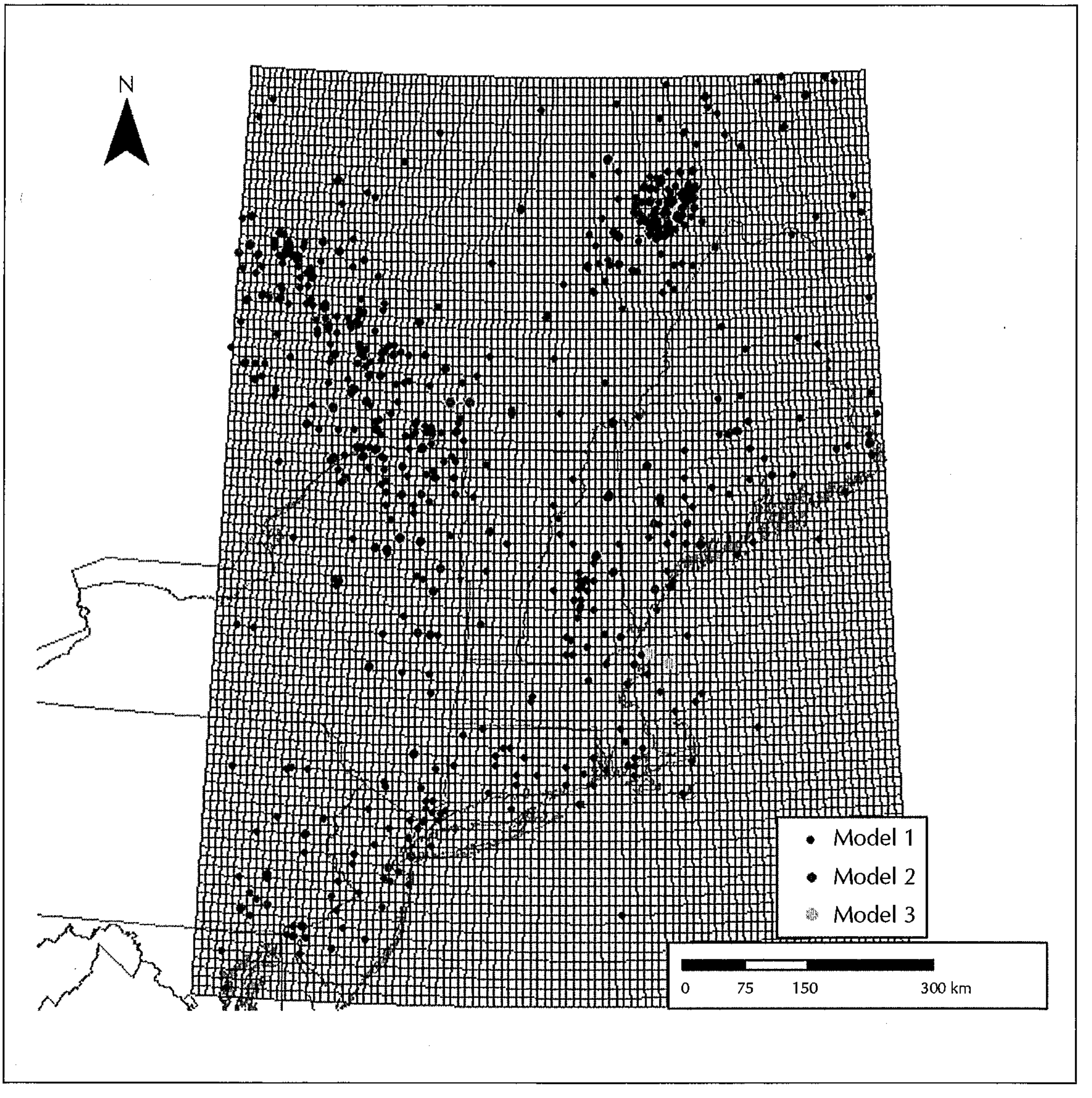

FIGURE 2. Events included in historic seismicity models.

for later use by the seismic hazard subroutine.

The seismic hazard subroutine was run for each model to collect the cell coordinates and smooth the count. The user was prompted for the time period and the minimum magnitude of the catalog for the model and for the SRAF. The source area for this study overlaps regions with different SRAFs. For this study, the SRAFs derived by Mueller *et al.* for the east coast of the United States were used for the entire source area.[11] Factors of 1.27, 1.15 and 1.58 were multiplied by the smoothed counts for Models 1, 2 and 3, respectively, in order to adjust the seismicity. Different factors were used by the 2002 Frankel *et al.* study north of the St. Lawrence River.

The subroutine looped through all 10,000 grid cells and called a function that determined the PGA value with a probability of exceedance of 10 percent in fifty years at each grid cell. The function selected trial ground motions and calculated its rate of exceedance, which was then compared to the rate of exceedance corresponding to 10 percent probability of exceedance in fifty years using a

Poisson distribution. The annual rate of exceedance, λ, for a ground motion, u_0, was calculated for a specific cell after Frankel, as follows:[4]

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

This equation represents the sum of the product of the annual rate of exceedance and the probability of a ground motion exceeding u_0, for discrete distance and magnitude bins represented by distance k and magnitude l, respectively. The annual rate of exceedance is a form of Gutenberg-Richter recurrence law, which expresses the logarithm of the rate of exceedance as a linear function. The "*a* value" is the intercept calculated by taking the logarithm of the adjusted, binned count, N_k, divided by the catalog time period, T. The "*b* value" in the recurrence law is the slope of the equation and is independent of the magnitude used to calculate the *a* value. The early Frankel *et al.* study used a *b* value of 0.95 for the CEUS, except for a 40- by 70-kilometer ellipse around Charlevoix, Québec, where the value of 0.76 was used.[5] 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. 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. Distance bins of 10-kilometer increments were used to cover distances up to 500 kilometers and represented by the midpoints of the 10-kilometer intervals.

For Model 4, the entire source area was treated as a uniform source zone.[4] Therefore, the ground motion for every cell from this model is equal. The 1996 Frankel *et al.* study 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.[5] That study normalized this count by area and disaggregated so an existing seismic hazard code could be used without modification. 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 selected following the suggestion by Frankel that the reference magnitude and time interval selected by the 1996 Frankel *et al.* study for Model 4 underestimated the hazard of large events. Theoretically, there should be no difference between the two approaches to Model 4 because the logarithm of the annual rate of exceedance for earthquakes of a given magnitude varies linearly with magnitude. These nine unadjusted events, normalized by dividing by 10,000 cells and the average cell area (which was estimated to be 88 square kilometers) represented the cell count. Since the count was constant for all cells, no smoothing was required. The same general procedure used for the historic seismicity models was used for Model 4, but calculations were only performed at two locations to ensure that the values were the same. In addition, 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 gridded ground motions for each model were factored according to Figure 1 to create the largest weighted average, which was plotted spatially in GIS. This plot resulted in contour maps that could be directly compared with the 2002 USGS data at the same locations, allowing an analysis of the procedure.

Results

Comparison of the New England map with the published USGS map demonstrated the conformance of the procedure used in this study with that used to develop the national seismic hazard maps, as well as the effect of differences between the two procedures. The gridded seismicity database from the 2002 USGS data was utilized to provide the primary graphical and numerical comparisons with the results from this study.[15] Figure 3 is the total seismic hazard map for New England as calculated in this study.

Figure 4 is a plot of the 2002 gridded PGA values from the national seismic hazard maps.

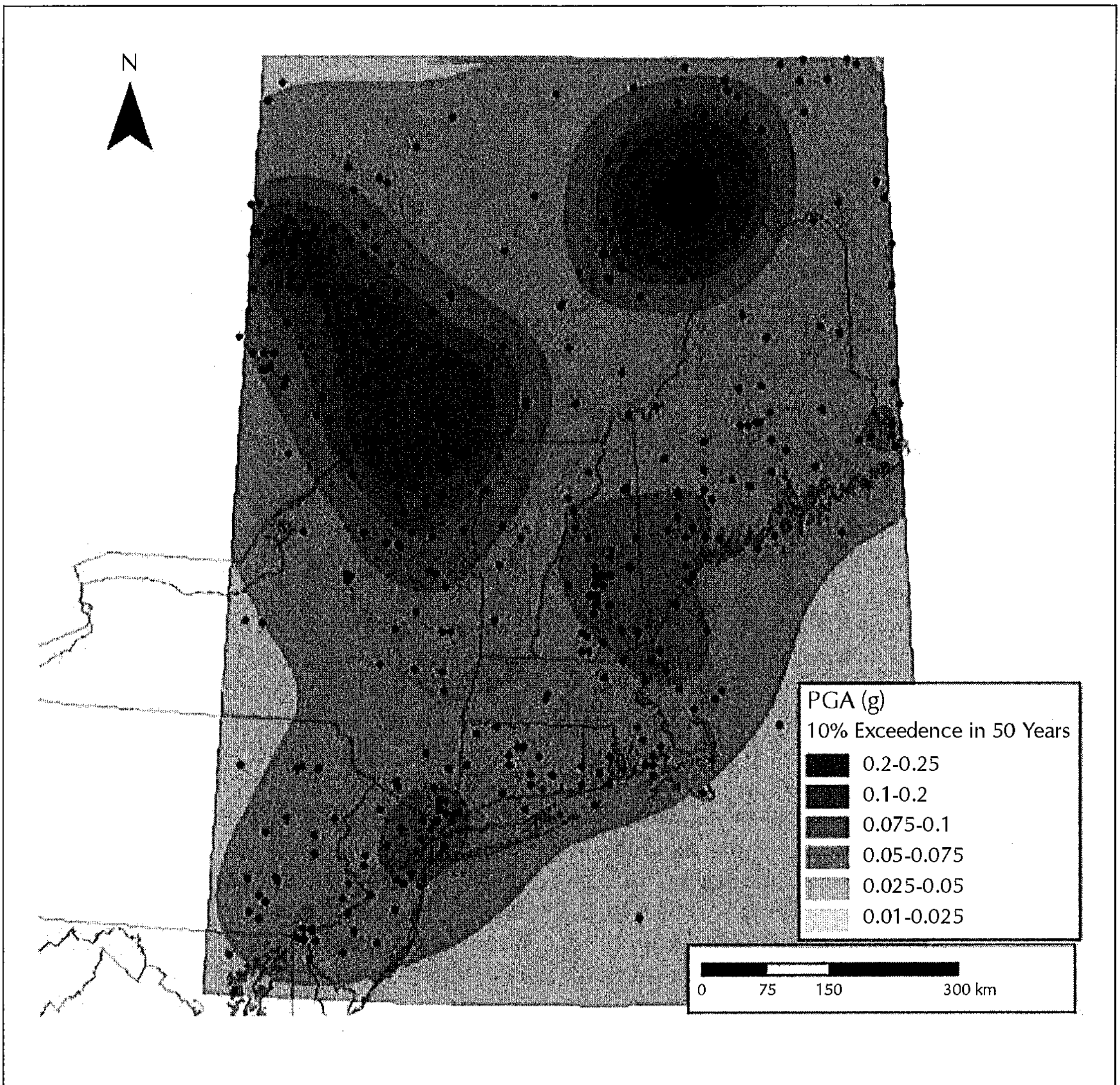

FIGURE 3. Total seismic hazard, adjusted historic seismicity.

The similarity between the maps shows that the procedure used to develop the New England map produced results very similar to the 2002 USGS map. The peaks centered in southern New York and New Hampshire shown in Figure 3 are reflected by similar peaks in Figure 4 of slightly different size and shape. The New York peak is smaller in radius in Figure 4. The 5 percent g contour of the New Hampshire peak does not extend as far east or southeast in Figure 4 as in Figure 3, but it does extend northwest to connect with the northeast-southeast peaks from the northern Adirondacks into Québec. In Figure 4, this peak area is connected to the Charlevoix peak by an area between 5 percent g contours. The Charlevoix peak has a large area of PGA greater than 27 percent g in Figure 4 (which is not observed in Figure 3). Figure 4 lacks a peak at Passamaquoddy Bay, Maine. The general trend is that the maps from this study, as seen in Figure 3, show slightly higher PGA in the southern portions of the map and lower PGA in the northern parts of the source area compared to the 2002 USGS maps.

The differences between the 2002 USGS gridded PGA values and the cell values plotted in Figure 3 were calculated and are plotted

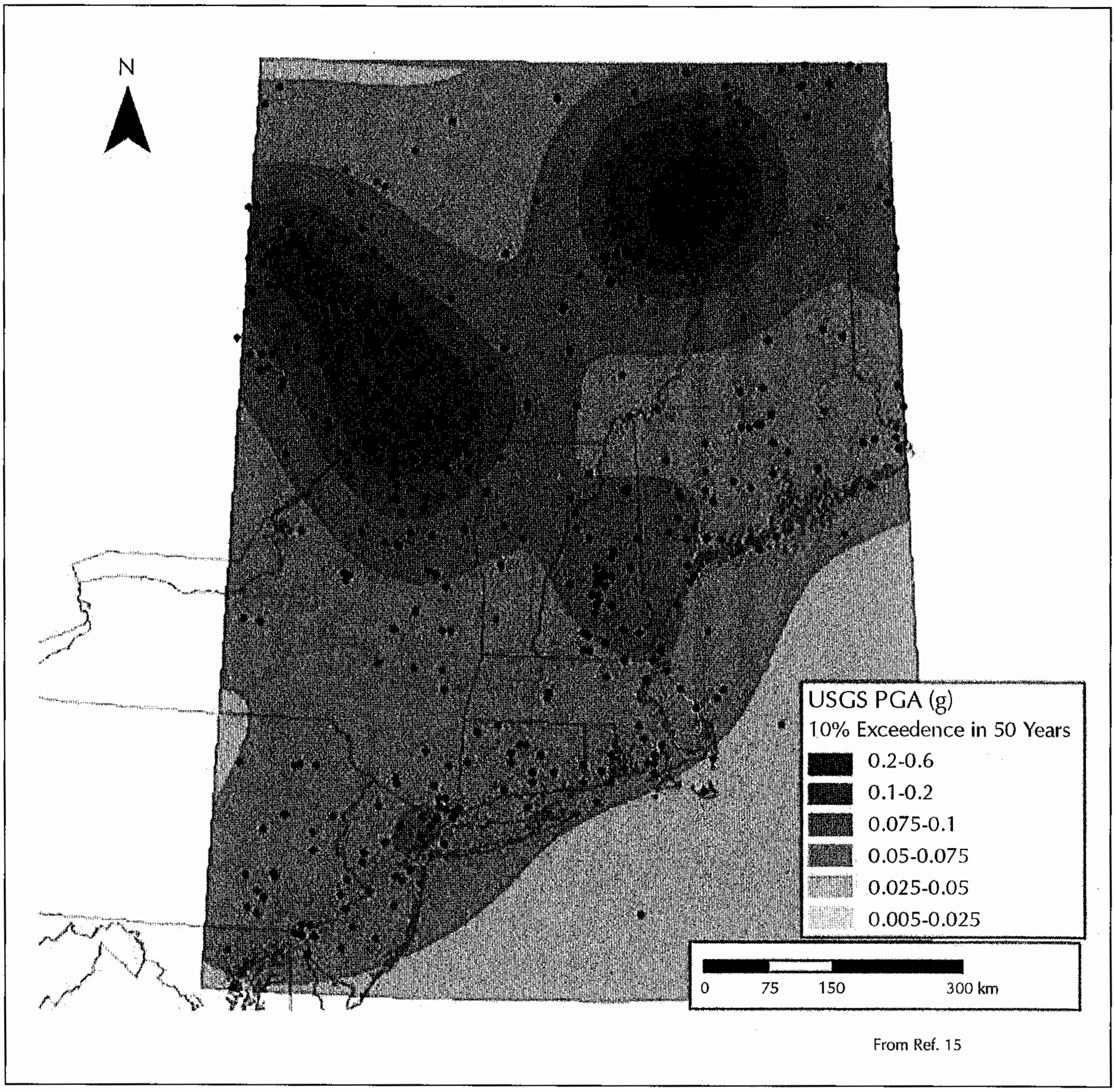

FIGURE 4. Total seismic hazard.

in Figure 5. This plot supports the observation that the southern part of the map is more consistent with the USGS values. Most of the map shows a difference of ±1 percent g. Since ground motions are typically expressed with a precision of whole percents of gravitational acceleration, this interval was judged to be effectively in "agreement." By inspection, over 75 percent of the map is within the "agreement" interval. The PGA off Cape Ann, Massachusetts, on the New York-Québec border and in the New York metropolitan area was calculated to be as much as 2.25 percent g greater in this study. Patches of Québec and Ontario fall in the +1 to +5 percent g region, especially in the northeast corner of the map, indicating higher ground motions from the USGS maps relative to this study. Differences as high as 40 percent g are observed around Charlevoix, where a different *b* value and different SRAFs were used. Interestingly, it is surrounded by an "agreement" region, which is surrounded by an area of +1 to +5 percent g differences between the maps.

Discussion

Having directly compared a custom seismic hazard map for New England with the 2002

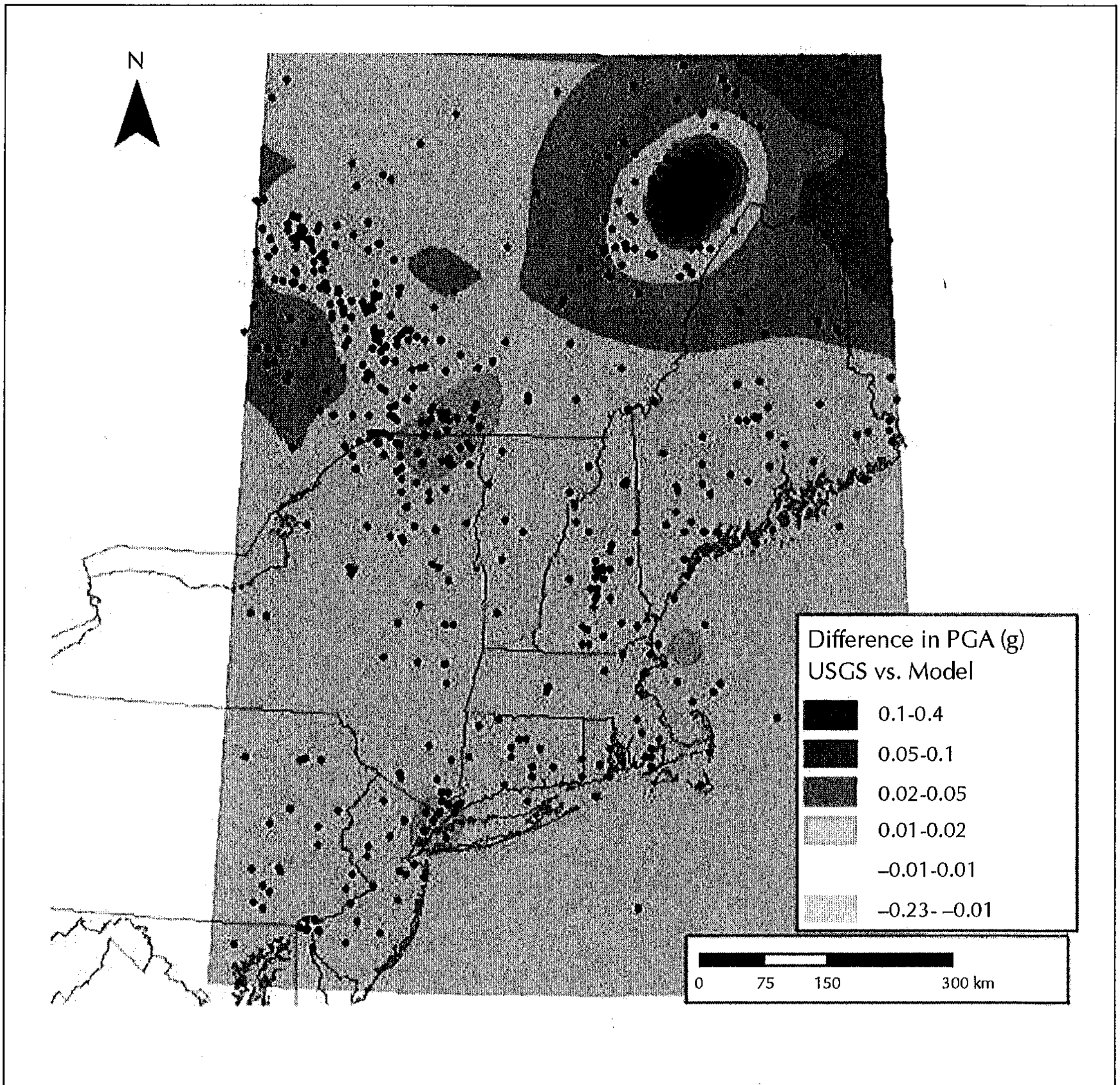

FIGURE 5. Comparison of total hazard maps with USGS data, adjusted seismicity.

national seismic hazard maps, 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 these parameters have relatively observable effects and are well documented. Less obvious effects, including changes in the logic tree and the internal workings of the hazard calculation, can be considered with less certainty.

The single largest modeling assumption encountered in this study is the use of SRAFs. SRAFs of 1.27, 1.15 and 1.58 were applied to the spatially smoothed historic seismicity of Models 1, 2 and 3, respectively. Much of the significant differences between the New England and USGS maps appear to be related to the choice of SRAFs. The SRAFs used in this study were those from Mueller *et al.* for the east coast of the United States.[11] 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[11]) and Charlevoix (where factors of 1.80, 1.80 and 1.36 were provided for Models 1, 2 and 3, respectively, and a lower b value of 0.76 was used). Using the generally smaller east coast factors resulted in a serious underestimation of PGA north of the St. Lawrence, which appears to be the cause of most of the disagreement between the northern portions of Figures 3 and 4.

The effect of the earthquake catalog used for a seismic hazard analysis can be evaluated by examining the contour shapes of maps using different catalogs. Seismic hazard is based on the rate of events occurring on a source. Adding years to a catalog time period will generally make an analysis more representative, but it will also locally redistribute hazard, thus reducing the seismic hazard near temporally and spatially isolated events. Adding events from 2002 and early 2003 to the catalog in this study produced no perceptible effect.

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. The selection of the source area is a significant potential source of error 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 be logically underpredicted. A region of underprediction relative to the USGS map would be therefore 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. Figure 2 shows few events on the perimeter of the source area that could be part of an earthquake cluster of significant hazard. Most of the perimeter of the map appears to be with ±1 percent g of the 2002 USGS values.[15] 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 2002 USGS map may be related to the exclusion of events near Miramichi, New Brunswick, although it is not specifically indicated on any specific model.[15] The exclusion of a cluster near Buffalo was observed to result in an underprediction over a small area of Model 3, although this underprediction did not appear on the averaged maps. Therefore, it would appear that the size of the source area is unimportant as long as it is located correctly. The source area must include a representative area that is likely to contribute significantly to the hazard, but need not include all areas of low hazard.

The choice of ground motion estimators is not expected to be a significant source of difference between the New England map and the 2002 USGS map because the same attenuation relations were used. The choice of attenuation relation is not, however, insignificant. The Atkinson and Boore relation significantly overpredicts ground motions of the scale typically found in New England because, for simplicity, a quadratic form, rather than a fifth order polynomial, was used to describe the modeled data.[7] Although attenuation relations are generally consistent for moderate to large earthquakes, they may be extremely inaccurate close to the epicenter, particularly for small events. The Campbell attenuation relation was designed to address this problem by using scaled west coast attenuation relations near the source, but this approach is relatively untested.[8] It is necessary to understand the limitations of any attenuation relation used in a specific analysis.

It would be expected that 1995 Frankel and the 1996 Frankel *et al.* studies used a consistent estimate of uncertainty for each map edition.[4,5] Frankel *et al.* used a lognormal standard deviation of 0.75 for the attenuation relations used for the 1996 map. However, it was not clear what standard deviations were made in the 1995 Frankel or 2002 Frankel *et al.* studies, requiring assumptions to be made for this study.[4,3] 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. Some of the differences between the maps in this study and in other publications likely resulted from the choice of standard deviation, but these variances could not be quantified. Such error would be expected to appear more randomly than the effects of other assumptions and would be difficult to identify.

The remaining sources of error remain buried in the procedure and the programming subroutines, where detailed definition was required in the absence of published guidance. An example of the 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 the 2002 Frankel *et al.* study or this study approximated the integral form of the exceedance rate.[3] It appears likely that this sort of error is responsible for some of the small, unexplained differences between the maps.

Conclusions & Extensions

A custom regional seismic hazard analysis was performed for the New England area following the procedures from the 2002 Frankel *et al.* study and was compared with the 2002 national seismic hazard maps.[3] The maps compare favorably, in spite of the fact that the analysis required assumptions and simplifications to account for incomplete documentation of the procedure and to facilitate programming. Both sets of maps share similar contours and PGA magnitudes, indicating that the same procedure effectively was used. The grid cell values for most of the custom New England map fall within ±1 percent g of the cell values from the 2002 USGS maps.[15] For the less than 25 percent of the cells that are not in the "agreement" range, much of the differences can be attributed to specific modeling assumptions and parameters.

The assumption resulting in the greatest difference between the New England map and the USGS map was the choice of SRAFs. 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[11]) resulted in different cell counts and, therefore, different recurrence rates. Errors of up to 5 percent g were attributed to the selection of SRAFs. Selection of the *b* value for the recurrence law proved to be even more critical (as shown by the high error in Charlevoix), but its effect was more localized and did not seem to affect New England hazard estimates.

Other errors (such as the effect of the source area boundaries, the coarseness of rate of exceedance estimate discretization and the assembly of the total hazard maps based on PGA rather than seismicity rates) were found to result in divergences of up to ±1 percent g. Although this amount is significant in terms of percent, 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.

Due to the resilience of the hazard calculation procedure, minor changes in the procedure (such as the assumptions made due to incomplete documentation) did not produce significant results. Larger changes were visible, but did not radically alter results. This lack of effect on results means that the procedure may be reasonably simplified, refined or otherwise altered with low risk of unrealistic results because the procedure is inherently stable. Therefore, this procedure lends itself to customization to further refine the maps to account for region- or project-specific requirements.

A customized PSHA (such as one applied in this study) can be performed when site conditions fail to conform to the applicable design code, or when a variance to the code is desired. A complete seismic hazard analysis can be customized for the specific requirements of a given site or project, with the seismic loads determined directly from seismological data and models. Ground motions could also be calculated for probabilistic criteria that are unavailable in published maps. Although it would be prudent to run the analysis with a common rate of exceedance to check against published maps, once the analysis works properly any rate of exceedance could be selected to reflect the risk tolerance and design life of any project.

The 2000 International Building Code (IBC), which is intended to replace the model building codes used in jurisdictions across the United States, allows site-specific ground motion analysis.[16] A site-specific study is required to account for regional geology, seismicity and maximum magnitudes of events on known faults and source zones relative to the site-to-source distance. Near source effects and subsurface characteristics must be considered. The required design event is the maximum considered earthquake (MCE), which has an average return period of 2,500 years (2 percent probability of exceedance in fifty years). The design ground motion parameters are the 5 percent damped design spectral response accelerations at short period (SDS) and 1-second period (SD1) that can be used to define the design response spectrum. The design spectral response acceleration is two-thirds of the spectral response acceleration from the seismic hazard analysis and it must be greater than 80 percent the spectral response from the code procedure.[16,17] This custom PSHA methodology could be easily adapted to comply with IBC requirements by using the correct attenuation relations, probabilistic criteria and additional post-processing.

National seismic hazard maps will evolve as seismologists and engineers better understand the mechanics of earthquakes both at the edges and interiors of tectonic plates. It is hoped that the calculation procedure would continue to incorporate an extensive, but practical set of models to predict ground motion parameters. As shown in this study, a large number of models 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 maps balance these needs very well. Future maps should attempt to maintain this balance.

NOTES — *The GIS software selected for this study was ArcMap by ESRI. Visual Basic for Applications (VBA) programs were developed and run in Microsoft Excel to perform calculations. AutoCAD was the computer-aided drafting software used.*

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