GROUND MOTION SUITE SELECTION FOR BOSTON, MASSACHUSETTS

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ABSTRACT

This paper introduces a suite of ground motions selected for the Boston area that are based on earthquakes catalogued in the Nuclear Regulatory Commission (NUREG) database. Records from earthquakes recorded in Eastern North America or similar tectonic environment are scarce because the tectonic environment is generally stable and the distribution of strong-motion recording equipment in such regions worldwide is relatively sparse. The proposed suite of motions has been filtered from existing earthquake records based on peak ground acceleration (PGA), magnitude and frequency content according to criteria that reflect the latest information available from the United States Geological Survey (USGS). Records selected from the NUREG database had already been altered, according to seismological considerations, to resemble the characteristics of the tectonic environment in the Eastern North America. For comparison to the suites of recorded motions, a suite of 100 simulated motions was created to reflect as accurately as possible the deaggregation of the USGS probabilistic seismic hazard analysis (PSHA) for Boston.

Introduction

Previous attempts to develop Boston ground motions include work related to the Central Artery Tunnel (CAT) Project in Boston (DPW 1990), work completed during Phase II of the SAC project (Somerville et al. 1997) and a suite of ground motions developed by Somerville and Collins using deterministic methods and records from past earthquakes (Somerville, Collins 2003). As part of the seismic evaluation for the Boston CAT Project, a team of seismologists and engineers determined the Boston seismic hazard and simulated a single ground motion for Boston. The response spectrum for the simulated motion matches well with the current Uniform Hazard Spectrum (UHS) for Boston.

The SAC project, which was motivated by unexpected damage to steel moment frames during the 1994 Northridge Earthquake, was a joint venture of the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREe). The focus of the project was on providing design recommendations to the structural community as well as analyzing the nonlinear response of structures in three US cities: Boston, Massachusetts; Seattle, Washington;

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and Los Angeles, California, representing a wide range of seismic-hazard scenarios.

The records were selected to match their target spectrum exactly for structures with a period of 4 seconds. To achieve this exact match, the original records were scaled using factors that ranged from 0.27 to 9.58 (Somerville, et. al. 1997). Recent studies have shown that scaling introduces bias in the nonlinear response of structures and that the bias varies depending upon the properties of specific structures and earthquakes (Luco 2004). To avoid inaccurate and often unrealistic motions scale factors should be kept between 0.25 and 4 (Kramer 1996, Luco and Bazzuro 2004, Cornell and Iervolino 2005). The average scale factor applied to the ground motions for Boston in the SAC project was greater than 4, which may have caused the resulting ground motions to have unrealistic characteristics. While the scaled records match the target at 4-second periods, they grossly overestimate the short-period accelerations, a point that the authors of the SAC report (Somerville et. al, 1997) noted but did not address. The unrealistic results of this project prompted interest in finding a suite of appropriate ground motions for Boston from existing earthquakes records.

Most recently, a set of 10 ground motions for a 2475-year earthquake (approximately 2% in 50 years) in Boston were also developed by Somerville and Collins (1997). These ground motions were created using recorded time histories as well as deterministic wave propagation methods. When plotted against the average USGS probabilistic spectrum points, which they were created to match, the motions all fell above the UHS points. For a more detailed description of the methods used to create and scale the ground motions see Somerville and Collins (2003).

Depending on the design or research objective, different types of ground motions suites may be appropriate. A suite of seven records conforms with the most up-to-date NEHRP provisions (FEMA 2003). Standard performance evaluation procedures recommend suites of 10 or 20 records (FEMA 2000). The possibility that a non-ductile system may collapse under a large motion; however, suggests that performance evaluations for non-ductile systems should employ enough ground motions to characterize the distribution of these ground motions with sufficient accuracy. To this end, a suite of 100 records that reflects the USGS PSHA deaggregation for the Boston 2% in 50 year earthquake was produced artificially. In addition to reproducing well-established methods, this paper presents a filtering scheme that can be applied to existing ground motion data to select appropriate ground motions for a particular location. Comparison of these various suites shows that a central question for any suite of motions relates to the manner and extent to which their acceleration response spectra should vary with respect to the target UHS points.

**Tectonic Environment**

The tectonic environment in a region can affect the frequency content, duration and maximum acceleration of earthquake ground motions. Eastern North America (ENA) is located on a stable continental plate, which distinguishes it from the Western North America (WNA), which is located on a plate boundary. The bedrock in ENA is older and harder than the bedrock in WNA, which causes seismic waves to attenuate less rapidly, and as a result ground motions are felt over a broader region in ENA than in WNA for the same magnitude event. Ground motions in WNA also have less high frequency spectral energy because of the shallow crustal damping present in the softer rock. These differences in the bedrock cause seismic waves to propagate
differently through the two regions (McGuire 1997). Because seismic waves attenuate rapidly in WNA and in high seismic regions worldwide, ground motions are not often recorded at large distances (>100 km).

**Defining the Target Spectrum**

The UHS for a 2% in 50-year earthquake in Boston, Massachusetts was obtained from the USGS (USGS, Leyendecker, 2004) and was used as our target spectrum. The shape of the target defines the frequency content for an expected Boston earthquake and its amplitude defines the magnitude of the accelerations. Figure 1 shows the UHS points and the response spectra for the maximum considered earthquake (MCE) and the design earthquake, which is simply 2/3 of the MCE, used for Boston in the IBC. The UHS and the IBC spectra are developed for rock sites (IBC Site Class B), and rock motions were used as the target for this work. Motions developed for site class B can be amplified based on site-specific soil characteristics.

![Figure 1. Uniform hazard spectrum, IBC MCE Spectrum and IBC design spectrum for a 2% in 50-year earthquake in Boston, Massachusetts](image)

**Availability of Ground Motions**

Past studies have used amplitude scaling and/or spectral matching to modify ground motions to match the target spectrum (Malhotra 2003) or have simulated ground motions that have the desired characteristics for the specific analysis in question (Tremblay and Atkinson 2001, Wen 2001). The use of ground motions from past earthquakes is possible if the selection criteria are appropriate. Because events in regions with similar tectonic environments as Boston are rare and seismic networks in these regions are relatively sparse as compared to WNA, very few records have been recorded (Cosmos 1999). Additional challenges are that the few existing records are often at large distances, are the result of unusual events, e.g. 1988 Saguenay Earthquake (Atkinson and Boore 1995) or were recorded at sites with unusual soil condition e.g. dams - Franklin Falls Dam, North Hartland Dam, North Springfield Dam. Because of the scarcity of reliable records from ENA earthquakes, scaling or spectral matching of some type is necessary; however, the amount of scaling and the method in which it is implemented should be controlled to avoid unrealistic results.
Bounds for the Uniform Hazard Spectrum  
Because no recorded ground motion will match a target spectrum exactly without spectral matching, upper and lower bounds values were used for the UHS points to ensure that the amplitude of the response spectra of selected ground motions would be within an acceptable range of the target. Through discussion with researchers at the USGS, it was agreed that upper and lower bounds of approximately 2 and 0.5 were appropriate for this study (Frankel 2005).

Methods for Ground Motion Selection  
Many different methods for developing and selecting appropriate ground motions for a particular area exist. Records from past earthquakes can be used in areas where such records exist, ground motions records can be generated using deterministic models based on what is known or assumed about the tectonic environment and seismic characteristics of a region or ground motion records can be simulated using stochastic models (Boore 2003). The PSHA that ultimately produced the spectral accelerations used for design in ENA used a weighted average of the results from 5 different attenuation relationships. The attenuation relationships were developed using various methodologies and were weighted to produce the most plausible spectral accelerations. The 5 attenuation relationships used for the PSHA for ENA were Atkinson and Boore (1995), Frankel et al (1996), Toro et al. (1997), Somerville (2001), and Campbell (2003). The Atkinson and Boore, Frankel, and Toro attenuation relationships were all developed using the results of stochastic models. The Somerville attenuation relationship was developed using deterministic models and the Campbell relationship was developed using a hybrid method that incorporated both deterministic and stochastic models.

Selection of Ground Motions  
We selected ground motion records for an ENA suite from the database compiled using acceleration, velocity and displacement time histories from NUREG/CR-6728, a report prepared for the U.S. Nuclear Regulatory Commission (McGuire 1997). The database contains 1900 ground motions from 50 different earthquakes, most of which took place in California. Most of the earthquakes were recorded in WNA or in tectonic environments similar to that of WNA. To create ENA ground motions, WNA ground motions in the NUREG database have been scaled using theoretical transfer functions to adjust for source and attenuation differences between the two environments, as described in the report compiled by McGuire (1997). The database is separated into pseudo-tectonic environment: WNA and ENA.

We converted acceleration time histories from this database to response spectra using the Newmark Beta linear acceleration method with 5% damping. We calculated the square root of the sum of the squares (SRSS) of the response spectra for each pair of ground motions. This resulted in a single response spectrum representing the maximum response of each pair; we used this SRSS response spectrum for all further analyses.

We used several levels of filtering to select ground motions for Boston with appropriate frequency content and spectral accelerations. We considered records from the NUREG database if the PGA of both orthogonal horizontal components for a particular record was between 0.05g and 0.30g, which bound the target PGA value of 0.15g. We capped the moment magnitude at 7.5, which is the USGS standard for ENA (Frankel 2005). In selecting appropriate ground motion records, distance was not used as a factor because records from large magnitude
earthquakes at large distances are rare. Because of the scarcity of recorded ground motions from stable tectonic regions, we used ground motions from different tectonic regions if the ground motions matched the criteria for earthquake magnitude, PGA, frequency content, and duration. We determined that if a record matched all of the above criteria, then the energy content of the ground motion would be appropriate for an expected Boston earthquake.

Next, we filtered the records so that each response spectrum fell within the bounds at all 6 periods where UHS points existed. The number of records remaining after each step of the filtering procedure is shown in Table 1. After performing the filtering only 12 motions from 8 distinct earthquakes remained for the ENA motions and only 13 motions from 8 distinct earthquakes remained for the WNA motions. A suite of 7 ground motions from 7 distinct earthquakes was selected from each group by determining which combination produced the average with the smallest mean squared error when compared with the UHS points. While researchers disagree on how appropriate it is to match the average of the ground motions selected for the suite with all of the UHS points (Luco 2004), recent studies demonstrate the susceptibility of ENA structures to higher mode effects and changes in modal behavior due to non-linear action (Gryniuk 2006, Nelson, et.al 2006) Therefore, it is important that the ground motions are appropriate, in aggregate, for all structural periods.

<table>
<thead>
<tr>
<th>Filter Level</th>
<th>Number of Records</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENA</td>
</tr>
<tr>
<td>0 - Entire Database</td>
<td>1900</td>
</tr>
<tr>
<td>1 - PGA Bounds (0.05g to 0.3g)</td>
<td>294</td>
</tr>
<tr>
<td>2 - Tectonic Environment</td>
<td>185</td>
</tr>
<tr>
<td>3 - Magnitude</td>
<td>115</td>
</tr>
<tr>
<td>4 - Spectral Matching</td>
<td>12</td>
</tr>
</tbody>
</table>

The averages of the suites for the ENA and WNA are shown in Figure 2. The individual motions chosen for the ENA suite are shown in Figure 3 along with the UHS points, the upper bound and the lower bound for Boston. The mean squared error between the suite average and the UHS points (measured only where UHS points existed) for the ENA and WNA suites was 3.3% and 8.8%, respectively. The difference between the averages of the two groups lies mainly in the short-period range. This supports the idea that ENA motions have higher short-period accelerations than comparable WNA motions and validates our decision to use the motions that were altered to represent the conditions in the ENA.
Ground Motions developed using Atkinson & Boore 1995

Atkinson and Boore (1995) used the stochastic method to simulate ground motions which were used to update their previous attenuation relationship (Atkinson and Boore 1987, Atkinson and Boore 1995). The update was warranted as new data collected spurred new ideas and theories about the behavior and characteristics of Eastern North American (ENA) earthquakes. For example, the 1988 Saguenay, Quebec earthquake produced data that differed considerably from previous predictions of ENA ground motions. Specifically, the results did not agree with the Brune source model (Atkinson and Boore 1995). Also, newer research showed that wave propagation and wave attenuation were not properly modeled in the previous relationships. For a detailed description of the stochastic method or the relationships used, see Atkinson and Boore (1995).

Table 2. Magnitude Distance Relationships from Deaggregation

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Magnitude</th>
<th>Number of Simulations</th>
<th>Distance (km)</th>
<th>Magnitude</th>
<th>Number of Simulations</th>
<th>Distance (km)</th>
<th>Magnitude</th>
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<td>10</td>
<td>14.93</td>
<td>6.5</td>
<td>2</td>
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<td>32.41</td>
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<td>5</td>
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<tr>
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<td>172.13</td>
<td>7.0</td>
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</tbody>
</table>

We implemented the stochastic method and developed the ground motions for ENA using software created by David Boore and the parameters for the 1995 Atkinson and Boore attenuation relationship. As a result, we generated a set of 100 ground motions for a site on firm
soil (B-C sites). We determined the magnitude-distance event distribution, shown in Table 2, for the ground motions by using the results of the deaggregation for Boston, Massachusetts. The 100 individual motions, along with the average (shown with a heavy line) and the UHS points are plotted in Figure 4. Note that most of these motions fall below the UHS points for Boston at periods of 1 and 2 seconds, though it has been suggested that this model may underestimate the accelerations at a period of 1 second (personal communication, Frankel, 2005). The response spectra that have accelerations of over 4 g are the result of a magnitude 7 event at a distance of 11 km. While these high accelerations seem unlikely for the Boston area, they are reasonable for such a large event at a close distance. The fact that there are only 2 such motions out of 100 demonstrates that the likelihood of such an event is small.

![Figure 4: Simulations Created Using Parameters from Atkinson & Boore 1995](image)

**Discussion**

One of the main issues in finding an appropriate suite for ENA is how to bound the UHS values. We want to use bounds that will ensure that our suite does not deviate excessively from the UHS points; however, we want our suite to contain all of the possible scenarios. Figure 5 compares the bounds suggested by the USGS with the average response spectra we obtained from the simulations and the suite selection from the NUREG database. The average of both the suites fits well within the bounds. The average of the simulated motions falls below the lower bound at periods greater than 1 second, which suggests that the Atkinson and Boore (1995) attenuation relationship does not represent the average expected values at higher periods. The simulated motions that fell below the lower bound point at a 2 second period had accelerations more than 2 times less than the UHS point at that period. Because the UHS points are a combination of 5 attenuation relationships, the low values at long periods resulting from the Atkinson and Boore relationship were compensated for by higher values at those periods from other relationships. The upper bound used in our filtering scheme allows less than 20% of the motions to exceed it at each UHS point, which is warranted given the amount of uncertainty in predicting ENA motions.
Conclusions
Two suites, each with 7 motions from 7 distinct earthquakes, were selected from earthquake records in the database compiled by the U.S. Nuclear Regulatory Commission. The suites were selected so that the average of the response spectra for the 7 motions matched the Uniform Hazard Spectrum for Boston. A comparison of the suites demonstrates that ground motions in the ENA tend to have higher short period energy than those that occur in the WNA. The suites were selected using upper and lower bounds for the spectra to constrain the amplitude and frequency content. The bounds are validated by measuring the spread of accelerations at each UHS point produced from the ground motion simulations representing the deaggregation of USGS PSHA.

The large variation in acceleration response spectra values for the suite of 100 artificial motions reflecting the deaggregation of the USGS PSHA indicates the range of spectral accelerations that structures in Boston may be subjected to for the 2% in 50 year occurrence. Such a suite should prove useful for developing confidence intervals for structural performance. While structures may be analyzed to collapse under the largest motions; these motions have very low probability of occurrence. Conversely, collapse under a suite of 7 or 12 earthquakes suggests that the design of the structure is insufficient without providing any information on the likelihood of the individual earthquake that caused the collapse. While some researchers have proposed relying on the median response for smaller suites that produce collapse (Shome and Cornell 2000), this does not provide clear information regarding the level of risk associated with such collapse.

Future Work
In future work, the suites of motions presented herein, and the 100 motions created using the stochastic method to match the deaggregation of the USGS PSHA will all be applied to a single
degree of freedom (SDOF) structural system. The response of the SDOF system to these motions will be compared to evaluate the effectiveness of the filtering process in finding ground motions for a given location. Further work to refine the bounds for the acceleration response spectrum values for the smaller suites of motions should take into account the variation in structural response under the entire range of motions developed directly from the USGS PSHA deaggregation. A combination of non-linear system and SDOF analyses under these motions should make it possible to assign a confidence level to certain bounds for deterministic analyses.

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References


CCA Dynamic Solutions, LLC, 2004. website located at www.seismicmotion.com


Frankel, A., Personal Communication, 6/05-9/05.

Gryniuk, M.C., 2006. Seismic Performance of Low-Ductility Chevron Braced Steel Frames in Moderate


Luco, N. and Bazzurro, P. *Effects of Earthquake Record Scaling on Nonlinear Structural Response*, Report on PEER-LL Program Task 1G00 Addendum (Sub-Task 1 of 3), 2004.


