FINAL TECHNICAL REPORT

USING A BAYESIAN FRAMEWORK TO QUANTIFY PARAMETER UNCERTAINTY AND MODEL OPTIMIZATION FOR STRONG GROUND MOTION ATTENUATION RELATIONSHIPS

NEHRP Award No. 06HQGR0044

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Abstract

Ground motion attenuation relationships estimate the median and variance of ground shaking as it decreases with distance from an earthquake source. Current relationships use "classical" regression techniques that treat the input variables or parameters as exact, neglecting the uncertainties associated with the measurement of moment magnitude, site to source distance, and thirty meter shear wave velocity. This leads to a poorly defined model standard deviation and poorly constrained estimates of ground shaking away from the median towards the tails of the distribution. This research incorporates parameter uncertainty into the regression using Bayesian statistics. The results of including parameter uncertainty in ground motion attenuation relationships are, a) an improved understanding of the uncertainties inherent in the phenomena, b) a reduced and better defined model standard deviation, c) an improved model fit of strong motion data, and d) a better constrained estimate of rare events associated with ground accelerations towards the tail of the distribution. Ultimately, a better-constrained estimate of strong ground shaking translates to more accurately engineered facilities.

Investigations

This project has been funded by both NEHRP and PEER (Pacific Earthquake Engineering Research center). PEER provided the initial year of funding, with the subsequent year of funding provided by NEHRP. A technical oversight committee through the PEER NGA (Next Generation Attenuation) Project offered guidance on this project. The technical oversight committee is composed of Yousef Bozorgnia (PEER center director), Tom Shantz (CalTrans), Norm Abrahamson (PG&E), and Brian Chiou (CalTrans). The joint funding through NEHRP and PEER, and the input from the technical oversight committee has provided strong support for this research. PEER has subsequently funded a third year of this project which should bring this research to completion.

This research can be divided into three sequential goals:

1) Develop and validate the Bayesian regression procedures that incorporate parameter uncertainty into the regression of attenuation relationship.
2) Quantify parameter uncertainty, or measurement error, associated with the independent variables in attenuation relationships.
3) Run Bayesian regression procedures on several attenuation relationships to determine the impact this procedure has on the resulting model standard deviation.

The research to date has been successful in achieving goal one, and in addressing components of goals two and three. The results are discussed in the following section.

Results

A fundamental component of this research was developing the Bayesian methodology, and validating this methodology. The mathematics of Bayesian regression for this application are presented in Moss and Der Kiureghian (2006). The methodology was first validated on simple linear regression examples and then expanded to multiple linear regression necessary for fitting a curve to attenuation data. An existing attenuation relationship by Boore et al. (1997) was used to validate the methodology. In the validation phase, the Bayesian regression methodology was used to duplicate the results found using “classical” regression. In this case the parameters were treated as exact, having no parameter uncertainty. Once this was successful the parameters were treated as inexact, having some predefined parameter uncertainty, and the Bayesian regression run again to determine the impact of parameter uncertainty on the results. The figure below shows the reduced model standard deviation that is a result of accounting for parameter uncertainty. In this case estimated parameter uncertainties was prescribed to the independent variables of moment magnitude, thirty meter shear wave velocity, and site to source distance.

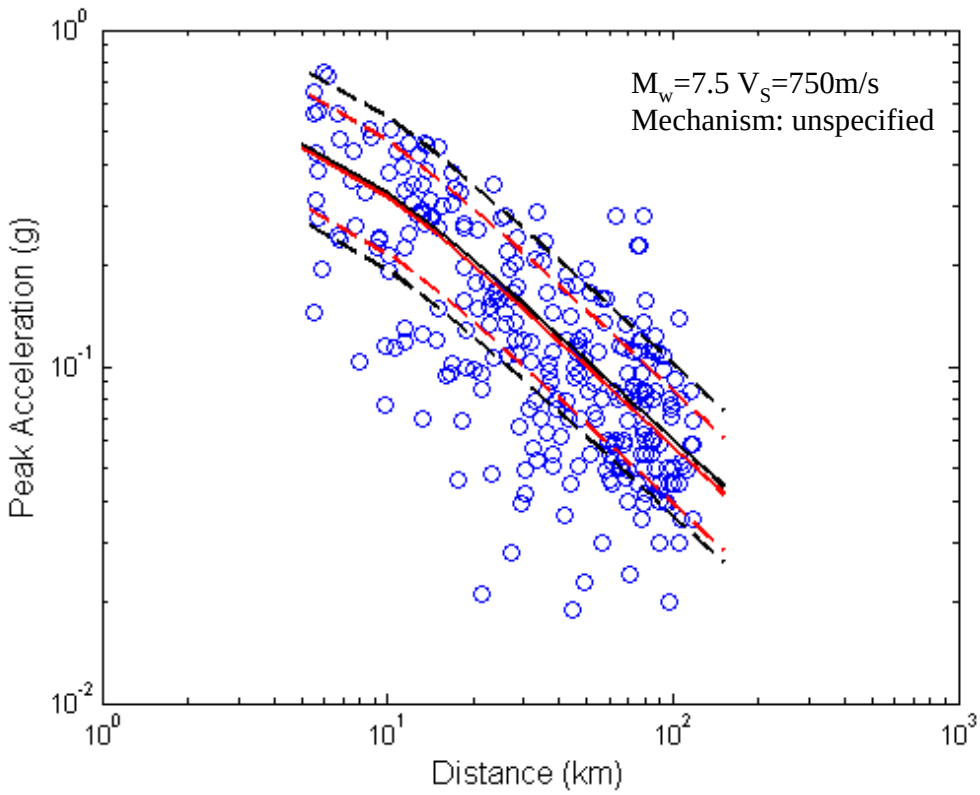

Figure 1. Comparison plot of attenuation relationship estimated using "classical" regression with exact parameters versus Bayesian regression that incorporates parameter uncertainty. The black curves are from Boore et al. (1997), the red curves from this study. Plus/minus one standard deviation curves are shown as dashed lines. (from Moss and DerKiureghian 2006)

After the methodology was validated, quantifying the specific parameter uncertainties of the independent variables was the next goal. This step can be rather difficult depending on the nature of the independent variable, the amount of data available for quantifying the uncertainty, and the nuances associated with this type of analysis. I along with the PEER oversight committee determined that uncertainty associated with thirty meter shear wave velocity (VS30) was of primary importance and that this is where the bulk of the research effort would be dedicated.

To quantify measurement uncertainty of thirty meter shear wave velocity there were several steps involved. A literature review was conducted to collect as much data as exists on VS30 measurements. Two types of data were collected; 1) data where researchers performed multiple measurements at the same site using the same equipment which provides information on precision of a single method, and 2) data where researchers performed multiple measurements at the same site using different equipment which provides information on accuracy. Many researchers were contacted to collect the information and were queried about their thoughts on measurement uncertainty.

The results of this portion of the research are now being published in the Bulletin of the Seismological Society of America. In that manuscript (Moss 2008), the three primary VS30 measurement methods (invasive, non-invasive, and correlated geologic units) used for site classification in attenuation relationships were emphasized. The results indicate that invasive methods (downhole, suspension logging, seismic cone penetration testing) have the lowest coefficient of variation (standard deviation/mean) which is on the order of 1-3%, but have a bias that is a function of soil disturbance the invasive methods cause. Non-invasive methods have more than twice the coefficient of variation as invasive methods, on the order of 5-6%. And correlated geologic units have a coefficient of variation on the order of 20-35%. These results do not include any spatial variability which increases the uncertainty with distance.

The figure below (Figure 2) shows the results of intra-method variability. This is the measurement uncertainty associated with each test method, found by repeated measurements at the same location. Intra-method variability can be a function of a number of different things (e.g. different operators, different inversion software, equipment sensitivity, data processing differences, etc.) which are all epistemic in nature. This measurement error along with the bias that exists between methods is quantified and identified explicitly in Bayesian regression, thereby separating it from uncertainty that is aleatory or inherently random in the attenuation phenomena.

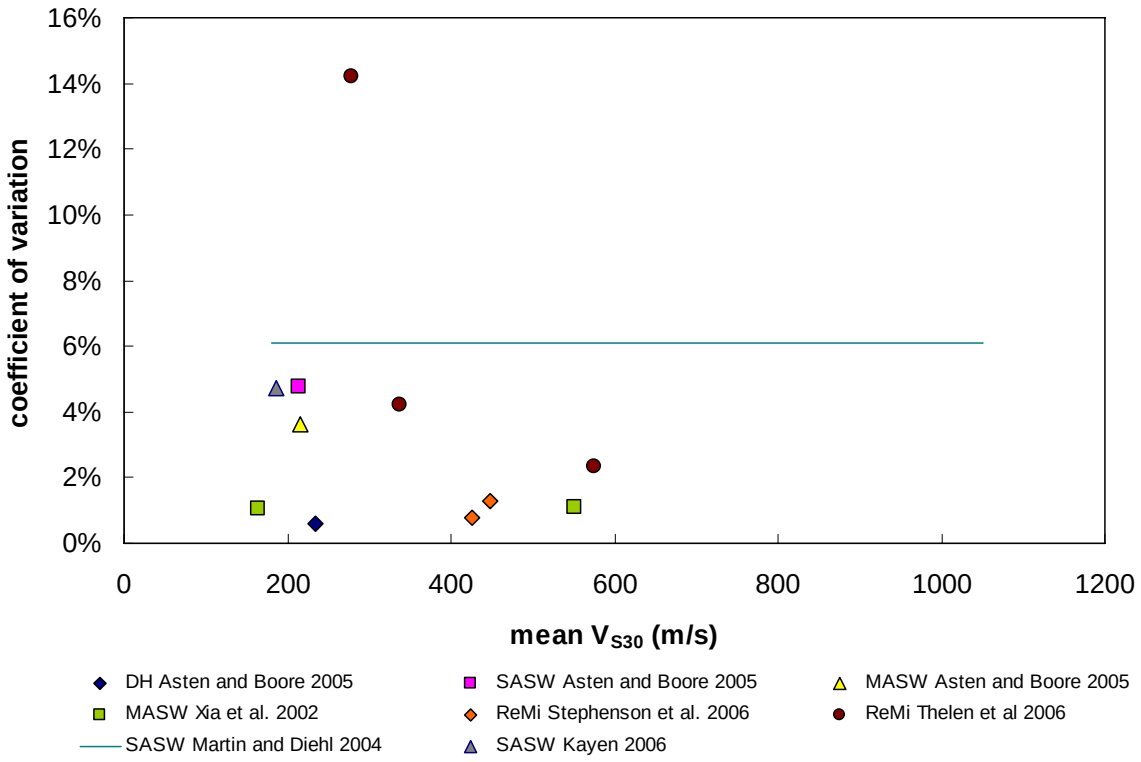

Figure 2. Results from various studies showing intra-method variability for different VS30 measurement methods. (from Moss 2008)

The independent variables of moment magnitude and site to source distance are currently being explored as this research continues for a third year. The quantified uncertainty for these parameters will be presented in later publications and a final PEER report. Preliminary results indicate that moment magnitude has two types of measurement uncertainty, one that is magnitude dependent and the other magnitude independent. Site to source distance has a fixed measurement uncertainty that can become influential and ambiguous when dealing with near fault ground motions.

Bayesian regression has been used to model one of the recent NGA attenuation models by Chiou and Youngs (2006). Preliminary results for a suite of spectral periods are shown in Figure 3 presenting the influence of including VS30 parameter uncertainty. These results show that the site dependent sigma (the site dependent standard deviation which is in natural log units) can be reduced by 4% to 9% as a function of the period by including the VS30 parameter uncertainty in the analysis. In other words the parameter uncertainty from VS30 makes up 4% to 9% of the sigma as estimated using "classical" regression. Including parameter uncertainty from moment magnitude and site to source distance, based on results from the initial feasibility study, promises to produce similar reductions in sigma. These reductions can result in significant differences in the predicted ground motion for rare events that are at two or more sigma from the median.

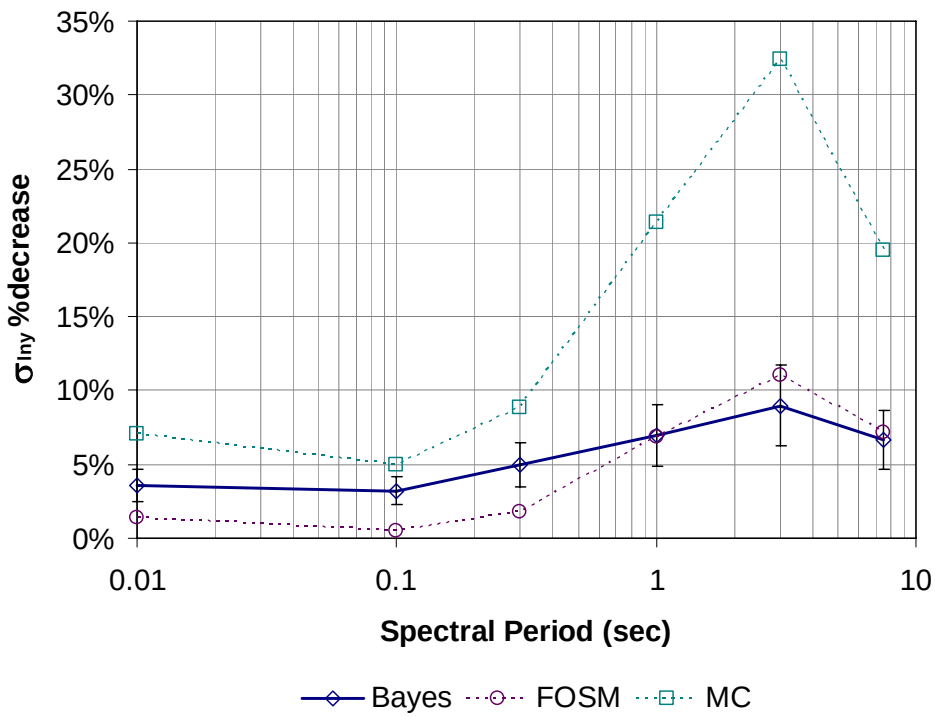

Figure 3. Preliminary (unpublished) results showing reduction of the site dependent sigma by including VS30 parameter uncertainty in the regression procedure using Bayesian regression. The Bayesian regression results are compared to FOSM (first order second moment) results and MC (Monte Carlo simulation) results. Note that the MC results are not considered reliable in this particular analysis because of a bimodal response in the functional form that resulted in inordinately high standard deviations. (from September 2007 PEER technical oversight committee meeting).

Plans for this project in the upcoming year will focus on two main items. The first is to run this analysis on another NGA attenuation model to compare results. The second is to include parameter uncertainty from moment magnitude into the analysis. The entire project should be completed by 2009 with all the results compiled into one PEER report. The results will then be disseminated in the form of one or two journal publications.

Non-technical Summary

This research seeks to separate measurement error (i.e., parameter uncertainty) from uncertainty that is inherent in the physical phenomena of seismic wave attenuation. By separating these two types of uncertainty, and modeling seismic wave attenuation using higher order regression techniques, more accurate predictions of ground motions can be obtained. This improved accuracy is particularly important for predicting seismic ground motions for rare events, or events that tend to be infrequent but can result in very large ground shaking. This research will result in lower more realistic predicted ground shaking for rare events.

Reports published

To date there have been two publications from this research. The first (Moss and Der Kiureghian 2006) is a methods paper that outlines the mathematics of Bayesian regression and presents a feasibility study using a published attenuation relationship. This paper was presented at the San Francisco conference commemorating the 1906 Earthquake. The second (Moss 2008) focuses on the measurement uncertainty associated with thirty meter shear wave velocity. This publication is currently in press at the Bulletin of Seismological Society of America. Both publications are included along with the submission of this final report.

References Cited

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