Region-specific ground motion relations for the Pacific Northwest
00-99HQGR0021

Gail M. Atkinson
280 McLean Ave.
Arnprior, ON K7S 3T2
(613) 623-3240
gma@ccs.carleton.ca

Program Elements: I, II

Key Words: Strong ground motion, Regional seismic hazards, Engineering seismology, Wave propagation

There is growing recognition of the earthquake hazard from both crustal and subduction earthquakes in the Pacific Northwest (PNW) region. A priority task to enable reliable seismic hazard estimation for the region is the development of region-specific ground motion relations, which predict average ground motion amplitudes (response spectra and peak ground acceleration and velocity) as simple functions of earthquake magnitude (moment magnitude, **M**), focal depth, and distance. These relations may be different for different types of events, such as shallow crustal, in-slab and interslab (subduction thrust) earthquakes. At present, it is generally assumed that ground motions from shallow crustal events in the PNW may be predicted using empirical ground motion relations developed for California, while ground motions from large subduction events may be predicted based on empirical relations developed from a global subduction database (eg. Frankel et al., 1996). These assumptions, born more of necessity than knowledge, do not appear to be supported by regional ground motion data. For example, high-frequency ground motions from moderate (**M**5.5) California earthquakes are consistent with an average 'Brune stress parameter' of about 100 bars (Atkinson and Silva, 1997, 2000), while similar studies for moderate shallow Cascadia events report an average stress parameter of only 50 bars (Atkinson, 1995; Atkinson and Boore, 1997). The **M** 5.1 Duvall, Washington event of 1996 and the **M** 4.3 Georgia Strait event of 1997 are characterized by stress drops of 70 bars and 45 bars, respectively (Atkinson and Cassidy, 1999). This suggests that, on average, California ground motion relations may overestimate the high-frequency motions from shallow crustal earthquakes in the Cascadia region by as much as a factor of two at near-source distances. On the other hand, the attenuation of high-frequency motions from shallow crustal events in Cascadia may be slower than in California, creating a compensating effect. Clearly, it is important to understand regional differences in ground motion generation and propagation, in order to assess their implications for seismic hazard.

For the deeper subduction earthquakes, it is standard practice to use empirical ground motion relations developed entirely from the global database (eg. Youngs et al., 1997). It is therefore important to address the question of whether the global database provides representative motions for the Cascadia subduction zone. This can be done by comparing ground-motion data from moderate events in the PNW to recordings of similar events in other data-rich subduction regions, such as Japan. Use of regional ground motion data may be important in understanding the extent to which empirical ground motion relations, based on a global subduction database, are applicable to the PNW. It is also important to update the global subduction strong-motion database to improve our understanding of subduction ground motions on a global scale (eg. the Youngs et al., 1997 database does not include events more recent than 1989).

The current project is developing region-specific ground-motion relations for both crustal and subcrustal events, using both regional seismographic data and global subduction databases.

Global Subduction Data Analysis

Ground motion relations for subduction zone earthquakes are an important input to seismic hazard analyses for regions affected by the Cascadia subduction zone (Washington, Oregon and British Columbia). There is a significant hazard potential from great thrust events along the subduction interface, and from large events within the subducting slab. A response spectra database has been compiled from thousands of strong motion recordings from events of moment magnitude (**M**) 5 to 8.3 occurring in subduction zones around the world, including both interface and in-slab events. The large dataset enables better determination of attenuation parameters and magnitude scaling, for both types of events, than has previously been possible. Soil response parameters, including nonlinear effects at strong levels of shaking, can also be determined from the data.

Preliminary regression of the dataset has been performed using a two-step regression procedure (Atkinson and Boore, 2000). The adopted preliminary functional form is:

$$\log PSA = c_1 + c_2 (\mathbf{M}-6) + c_3(\mathbf{M}-6)^2 + c_4 I_{type} - \log R - c_5 R - c_6 I_{type} R + S \qquad (1)$$

Where: PSA is 5% damped pseudo-acceleration in cm/s^2, average horizontal component

- $\mathbf{M}$ = moment magnitude
- I_{type} = 0 for interface events, =1 for in-slab events
- $R = \sqrt{(D_{fault}^2 + \Delta^2)}$ with
  - D_{fault} = closest distance to fault surface
  - $\Delta = 0.00724\ 10^{0.507\mathbf{M}}$
- S = soil response term, = 0 for rock (NEHRP site classes A or B, $\beta>700$ m/s), or
- $S = a_1 + a_2 \log PSA_{rock}$ for soil, where a_1 and a_2 are determined for site classes C ($360<\beta<700$), D ($180<\beta<360$) and E ($\beta<180$ m/s)

The distance variable for regression, R, is approximately equal to the average distance to the fault surface. This distance measure depends on the closest distance to the fault and the earthquake magnitude; the magnitude-dependence of R arises because large events have a large spatial extent, meaning that even near-fault observation points are far away from most of the fault.

Soil motions generally exceed rock motions by a significant factor, especially for soft soils at low frequencies (as much as a factor of 3). Interestingly, nonlinear effects are suggested only for the soft soils, although there may be insufficient data in the appropriate magnitude-distance range to determine nonlinearity for the firmer soils. The results suggest that in-slab events cause greater ground motion amplitudes at close distances than do interface events of the same magnitude. However, this is countered by a much more rapid attenuation of in-slab motions with distance, as compared to interface events. The results indicate that the dominant contributor to seismic hazard at 1 Hz comes from the interface events, while at 5 Hz the in-slab events produce larger ground motions (assuming an event of **M** > 8 for the interface event, or **M** 7.0 to 7.5 for the in-slab event).

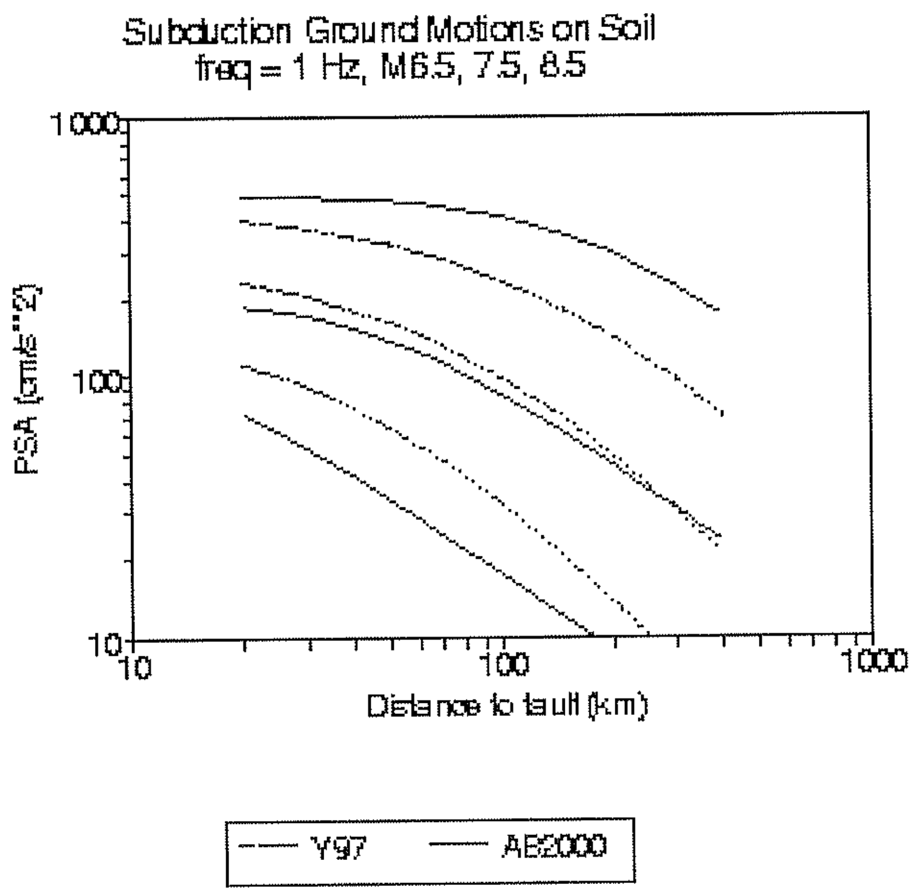

*FIGURE 1 - Preliminary regression results of Atkinson and Boore (AB2000) for intraslab ground motions on soil at 1 Hz, in comparison to the relations of Youngs et al. (Y97), for **M** 6.5, 7.5 and 8.5*

Figure1 shows the preliminary relation (AB2000) for interface events of **M** 6.5, 7.5 and 8.5, for soil sites (Class D) at 1 Hz. (Note: The x-axis is the closest distance to the fault, D_{fault}.) The relation of Youngs et al. (1997) is also plotted for comparison. The Youngs et al. (Y97) subduction relations are commonly used for seismic hazard analysis in the region; they were developed in the early 1990's from the much more limited dataset that was available at that time. The results of this study suggest larger amplitudes from interface events at large distances than do the Youngs et al. relations; this has important implications for hazard analysis. Figure 2 shows the AB2000 relations for in-slab events of **M** 6.5 and 7.5 at 5 Hz (also on soil sites); again, the Y97 relations are plotted for comparison. The AB2000 relations suggest lower 1-Hz amplitudes than the Y97 relations (not shown), while at 5 Hz the predictions of AB2000 and Y97 are very similar for D_{fault}<100 km.

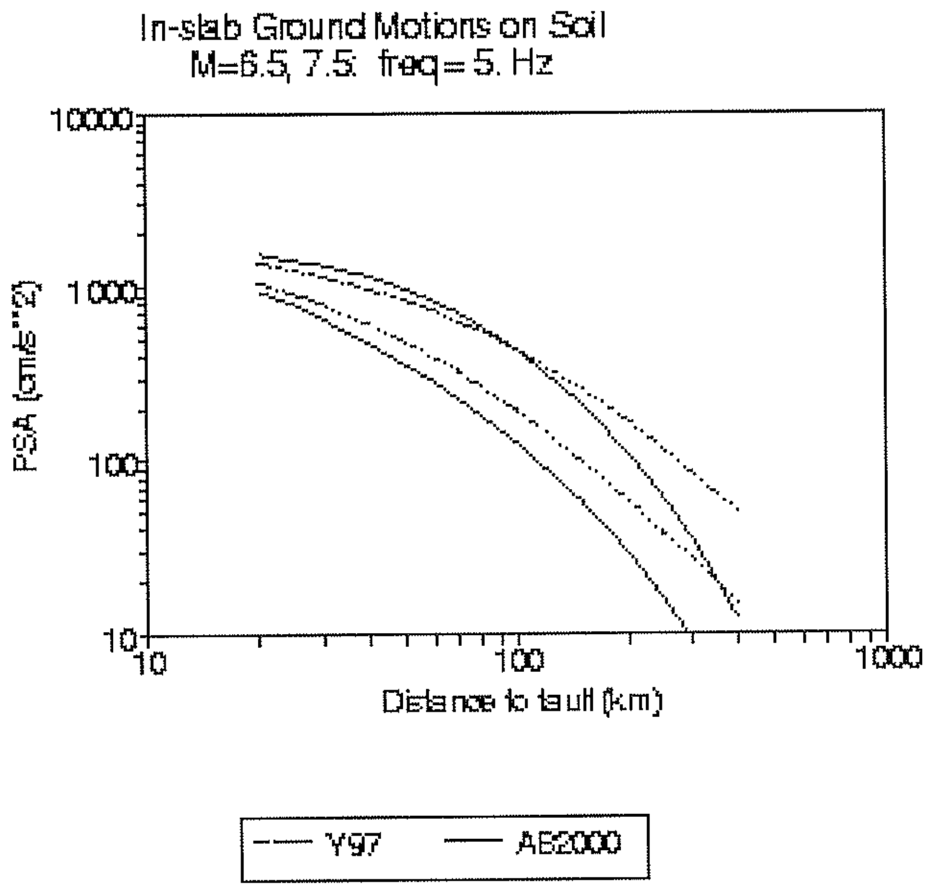

FIGURE 2 – Preliminary regression results of Atkinson and Boore (AB2000) for in-slab motions on soil, at 5 Hz, in comparison to the relations of Youngs et al. (Y97), for ***M*** *6.5 and 7.5*

Looking at a broad range of magnitudes and distances, the preliminary results suggest that the subduction ground motion relations of Youngs et al. (1997) may tend to overestimate the motions caused by moderate-to-large in-slab events (at all distances), but underestimate the motions from great subduction thrust events at large distances. This finding, if verified by more detailed regression analyses currently in progress, could have significant implications for seismic hazard analysis in the Cascadia region.

Regional Seismographic Data Analysis

Substantial improvements have been made in the PNW ground motion database for moderate regional events, by analyzing events recorded since 1995 on regional and broadband stations, as well as data from the 1993 Scotts Mills and Klamath Falls, Oregon events. About two dozen events have been analyzed to date, by obtaining regional broadband seismographic data and correcting them for instrument response to compute Fourier spectra and response spectra. This constitutes a significant addition to the previous database of PNW ground motions, which contains vertical-component recordings of 68 events of M 3 to 7 (Atkinson, 1995). Most significant is the improvement in data quality, due to the availability of 3-component broadband instrumentation. This greatly enhances the previous database, which was based largely on vertical-component short-period (1 to 10 Hz) network data. Important study events recorded on broadband instrumentation include:

- Scotts Mills, Or, 1993, M 5.6
- Klamath Falls, Or, 1993, M5.1, M 6.0 and M 5.9
- Robinson Point, Wa, 1995, M 5.0
- Duvall, Wa, 1996, M 5.3
- Offshore Vancouver Is., 1996, M 6.2
- Seattle, Wa, 1997, M 3.5
- Bremerton, Wa, 1997, M 4.9
- Okanogan, BC, 1997, M 4.6
- Georgia Strait, BC, 1997, M 4.6
- Yakima, Wa, 1998, M 4.0
- Satsop, Wa, 1999, M 5.8

The recent data, with improved bandwidth and 3-component coverage, are being combined with the previous PNW data and used to re-evaluate source and attenuation parameters in the Cascadia region, and their depth dependence. This evaluation will be empirical, based on the Fourier amplitude spectra of the records. It will establish how the amplitudes and frequency content of PNW ground motions vary with earthquake magnitude, depth, distance and event type. Source parameters such as moment magnitude and stress drop will be determined for each event, and an attenuation model describing geometric and anelastic attenuation will be defined. Ground motions from crustal earthquakes in the PNW will be compared to motions from crustal events in California and Japan, and to motions from subcrustal earthquakes, in order to develop region-specific ground-motion relations appropriate for each type of earthquake hazard in the Cascadia region.

Non-technical Summary

This project utilizes recent high-quality seismographic recordings of moderate earthquakes in the Pacific Northwest (PNW) to improve our understanding of the ground motion shaking hazard in that region. The new data will be used, in combination with previous regional data and a global subduction strong-motion database, to develop a model of ground motion generation and propagation in the PNW. This model will be employed to develop region-specific ground motion relations for the PNW. The development of region-specific ground-motion relations for the PNW is a high-priority task for NEHRP, as these relations are urgently needed in order to make reliable estimates of regional seismic hazard.

References

Atkinson, G. (1995). Attenuation and source parameters of earthquakes in the Cascadia region. Bull. Seism. Soc. Am., **85**, 1327-1342.

Atkinson, G. (1997). Empirical ground motion relations for earthquakes in the Cascadia region. Can. J. Civil Eng., **24**, 64-77.

Atkinson, G., and D. Boore (1997). Stochastic point-source modeling of ground motions in the Cascadia region. Seism. Res. L., **68**, 74-85.

Atkinson, G. and D. Boore (2000). Preliminary empirical ground-motion relations for subduction-zone earthquakes. Proc of the Workshop on Intra-slab hazards in the Cascadia subduction zone, U.S.Geol. Survey and Pacific Geoscience Centre, Sidney, B.C., Sept. 18-21, 2000.

Atkinson, G. and J. Cassidy (2000). Integrated use of seismograph and strong motion data to determine soil amplification in the Fraser Delta: results from the Duvall and Georgia Strait earthquakes. Bull. Seism. Soc. Am., **90**, 1028-1040..

Atkinson, G. and W. Silva (1997). Empirical source spectra for California earthquakes. Bull. Seism. Soc. Am., **87**, 97-113.

Atkinson, G. and W. Silva (2000). Stochastic modeling of California ground motions. Bull. Seism. Soc. Am., **90**, 255-274.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E. Leyendecker, N. Dickman, S. Hopper and M. Hopper (1996). National seismic hazard maps, June 1996. U.S.G.S. Open-file Rpt. 96-532.

Youngs, R., S. Chiou, W. Silva and J. Humphrey (1997). Strong ground motion attenuation relationships for subduction zone earthquakes. Seism. Res. L., **68**, 58-73.