Earthquake Ground Motion Selection

WA-RD 791.1

Steven L. Kramer
Pedro Arduino
Samuel S. Sideras

May 2012

Washington State
Department of Transportation
Office of Research & Library Services

WSDOT Research Report

Research Report
Research Project T4118, Task 69

EARTHQUAKE GROUND MOTION SELECTION

by

Steven L. Kramer
Pedro Arduino
Samuel S. Sideras

Department of Civil and Environmental Engineering
University of Washington

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Tony Allen
State Geotechnical Engineer

Prepared for

The State of Washington
Department of Transportation
Paula J. Hammond, Secretary

May 2012

1. REPORT NO. **WA-RD 791.1**	2. GOVERNMENT ACCESSION NO.	3. RECIPIENTS CATALOG NO

4. TITLE AND SUBTITLE

Earthquake Ground Motion Selection

5. REPORT DATE

May 2012

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

Steven L. Kramer, Pedro Arduino, Samuel S. Sideras

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
1107 NE 45th Street, Suite 535
Seattle, WA 98105-4631

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

T4118-69

12. CO-SPONSORING AGENCY NAME AND ADDRESS

Washington State Department of Transportation
Research Office, PO Box 47372
Olympia, WA 98504-7372
Research Manager: Kim Willoughby 360.705.7978

13. TYPE OF REPORT AND PERIOD COVERED

Final Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

Nonlinear analyses of soils, structures, and soil-structure systems offer the potential for more accurate characterization of geotechnical and structural response under strong earthquake shaking. The increasing use of advanced performance-based design and evaluation procedures will require consideration of long-return-period motions for all structures, especially in western Washington where high seismicity is a concern and long-return-period motions are likely to be strong enough to induce nonlinear, inelastic response in soil deposits and structures.

Nonlinear analyses require the specification of acceleration time histories as input; this requires the analyst to identify input motions that are consistent with the ground motion hazards at the site of interest. A considerable level of research effort has been directed toward the development of procedures for selection and scaling of earthquake ground motions for the purpose of using them in nonlinear structural analysis. This research has shown that structural response of buildings can be quite sensitive to the selection and scaling of ground motions used in nonlinear analyses. While the sensitivity of bridge structures to input motion characteristics has not been studied as explicitly as that of building structures, the response of bridges is also expected to be significantly influenced by input motion characteristics.

As a result, engineers have identified the need for software tools that will automate, to at least a large degree, the process of identifying suites of ground motions that are most appropriate for use in nonlinear response analyses. Along with this report, a piece of software, SigmaSpectraW, was created for WSDOT to do just that.

17. KEY WORDS

Earthquake, ground motion selection, SigmaSpectraW

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES	22. PRICE

DISCLAIMER

Table of Contents

Chapter 1

Introduction

The practice of seismic design has been developing rapidly over the past 20-30 years. Observations of response and damage in recent earthquakes, focused research supporting the development of performance-based design concepts, and developments in computer software and hardware have led to the increased use of numerical analysis in the seismic evaluation of existing structures and the seismic design of new structures. While structures have been designed using response spectra and modal superposition for many years, the use of nonlinear analysis has been increasing.

Background

Nonlinear analyses of soils, structures, and soil-structure systems offer the potential for more accurate characterization of geotechnical and structural response under strong earthquake shaking. Bridge and building codes require the evaluation of seismic response for ground shaking levels with relatively long return periods, e.g., on the order of 975 to 2,475 years. Also, the increasing use of advanced performance-based design and evaluation procedures will require consideration of long-return-period motions for all structures. In areas of low seismicity, long-return-period motions may not be particularly strong and response spectrum or equivalent linear analyses may be appropriate. In seismically active areas such as western Washington, however, long-return-period motions are likely to be strong enough to induce nonlinear, inelastic response in soil deposits and structures.

Linear and equivalent linear analyses can be accomplished with the use of response spectra alone, i.e., without explicit consideration of individual ground motion time histories. Site effects can be estimated using ground motion prediction equations (GMPEs) or amplification factors. Even equivalent linear site response analyses can be performed without time histories when random vibration theory (RVT) procedures are used. Nonlinear analyses, however, require the specification of acceleration time histories as input; this requires the analyst to identify input motions that are consistent with the ground motion hazards at the site of interest. A considerable level of research effort has been directed, particularly within the past 10 years or so, toward the development of procedures for selection and scaling of earthquake ground motions for the purpose of using them in nonlinear structural analysis. This research has shown that structural response of buildings can be quite sensitive to the selection and scaling of ground motions used in nonlinear analyses. While the sensitivity of bridge structures to input motion characteristics has not been studied as explicitly as that of building structures, the response of bridges is also expected to be significantly influenced by input motion characteristics.

Bridges, like other structures, tend to respond most strongly to loading at or near their natural frequencies (or periods). One simple approach to ground motion selection and scaling is to scale a suite of input motions to a target spectral acceleration at the fundamental period of the structure of interest. Such an approach will result in a suite of motions with no dispersion at the fundamental period of the structure (i.e., all of the scaled spectra would pass identically through the same point), but would result in significant dispersion at higher and lower periods. Higher periods are important, however, because the effective period of a structure tends to lengthen as damage occurs under strong shaking. Lower periods are also important because higher modes will respond to higher frequency (lower period) components of the motions. As a result, nonlinear analyses using motions scaled to match only a single point on a target spectrum will produce computed responses with high levels of uncertainty. The practical impact of that result is that more analyses (i.e., analyses using larger suites of input motions) will be required to predict the mean (or median) response with a given level of confidence. To obtain a good estimate of response with a relatively small suite of input motions, the motions should be selected with consideration of spectral shape – motions whose response spectra are consistent with the shape of the design spectrum over a range of periods both greater and lower than the fundamental period will provide improved predictions of structural response.

As a result of increased ground motion instrumentation and the natural occurrence of earthquakes over time, engineers now have access to thousands of recorded earthquake ground motions. These motions are from earthquakes that have occurred around the world, and represent a wide range of earthquake magnitudes, source-to-site distances, types of faulting, and site conditions. The process of selecting a small suite of motions that optimally match some desired target spectrum from these thousands of motions (and millions of combinations thereof) is extremely time-consuming when attempted manually. As a result, engineers have identified the need for software tools that will automate, to at least a large degree, the process of identifying suites of ground motions that are most appropriate for use in nonlinear response analyses.

Organization of Report

This report presents the results of a project undertaken at the University of Washington to provide the Washington State Department of Transportation (WSDOT) with software tools that aid in the selection and scaling of earthquake ground motions for geotechnical and structural response analysis. The following chapters describe the process by which appropriate software and data were collected and modified to provide WSDOT with a useful system.

Chapter 2 describes the results of a survey of available ground motion processing software and an evaluation of their relative suitability for use by WSDOT. Chapter 3 provides background on the types of target spectra used to define ground motion hazards – spectra used in current codes and spectra likely to be used in future codes. Chapter 4 describes the software recommended for use by WSDOT in ground motion selection and scaling, which is a modified version of an existing software program, and Chapter 5 describes a ground motion database that was assembled for use with the software described in Chapter 4. Chapter 6 presents a brief summary of the work completed for the project.

Chapter 2

Available Ground Motion Processing Tools

Several software tools for selecting and scaling earthquake ground motions are currently available. The tools all have different capabilities and operate with different databases and interfaces. All are relatively new so there is very little in the way of a track record with any of them. The following sections briefly review the three most significant tools that are currently available.

PEER Ground Motion Database

The Pacific Earthquake Engineering Research (PEER) Center has been collecting, processing, and archiving ground motion data for the past 15 years or so. In order to facilitate the original Next Generation Attenuation (NGA) research effort, PEER began collecting recorded motions from shallow crustal earthquake in active tectonic regimes and had Dr. Walter Silva of Pacific Engineering & Analysis, Inc. process all of the motions in a consistent manner. The motions were then posted online as the 2005 PEER NGA Database. The NGA database could be accessed and searched on the basis of source (magnitude, distance, style of faulting, etc.) and site (e.g., site class, V_{s30}) conditions. After some time, PEER contracted GeoMatrix to lead a team of researchers and practitioners in development of the Design Ground Motion Library (DGML), an anticipated stand-alone program that would allow the selection and scaling of ground motions relative to a target response spectrum. After an extended period of development, the decision was made to modify this effort from a stand-alone program to a web-based utility; a beta version of the PEER Ground Motion Database system was recently brought online at:

http://peer.berkeley.edu/peer_ground_motion_database

This link currently provides two options – searching and selecting motions without scaling, and searching and scaling ground motions.

The second option is most applicable to the problem at hand. The website allows a user to define a target spectrum; code- and GMPE-based options can be selected or a user-defined target spectrum can be entered. After entering the target spectrum, the user initiates a search of the PEER database for motions that are consistent with the target spectrum. Ranges of parameters including magnitude, style of faulting, duration, source-to-site distance, V_{s30}, and scaling factor can all be specified. In addition, the inclusion or exclusion of motions with near-fault pulses can be specified. Finally, the user can input a weighting function that allows the matching algorithm to consider matching at some periods to be more important than others when identifying motions. The program returns a list of 30 motions in ranked order of spectral match quality. Clicking on each motion produces time history plots of all three (fault-normal, fault-parallel, and vertical) components of acceleration (with one-click ability to plot velocities and displacements) and highlights the selected motion on a plot of all 30 response spectra. The selected motions are easily downloaded for subsequent use.

Advantages

The PEER system is well-designed and implemented, and the online utility is easy to use and runs relatively quickly – it is also freely available to all users. It has access to the PEER database, which is the most extensive and well-developed ground motion database in existence. The PEER database is maintained by PEER, so its updating requires no effort on the part of the user.

Disadvantages

The PEER system is constrained to use of the PEER database, which contains only motions from shallow crustal earthquake in active tectonic regimes. This restriction, which may be removed at some undetermined point in the future, presents difficulties for WSDOT in that the seismic hazards facing structures in many parts of Washington state are significantly influenced by potential Cascadia Subduction Zone (CSZ) earthquakes. Subduction zone events emanate from greater depths than crustal earthquakes, can be of considerably greater magnitude than crustal earthquakes, and can produce ground motions with significantly longer durations than crustal earthquakes.

SigmaSpectra

SigmaSpectra is a stand-alone computer program that selects suites of ground motions whose mean matches a target spectrum and scales the suite to match a target standard deviation. In this manner, SigmaSpectra can produce ground motions that tightly match a target spectrum (by entering a target standard deviation of zero) or match it with some desired level of dispersion. SigmaSpectra first selects suites of motions that match the target spectrum and then scales them to match the target standard deviation while maintaining the mean at the level of the target spectrum.

SigmaSpectra does not come with a pre-defined ground motion database (other than a small database used for the example problem in the program tutorial). It does allow the user, however, to develop a database that motions can be drawn from to develop ground motion suites. While development of a ground motion database can be time-consuming, the user has unlimited flexibility in selecting motions from different sources.

Advantages

SigmaSpectra is a public domain program for which the source code is available, thus allowing the possibility of modification to add useful features. The manner in which the ground motion data is made available to the program allows great flexibility in customizing the database for different tectonic environments – this advantage is particularly significant in a state with such different levels of sources of seismicity. The code is a stand-alone program that resides on the user’s computer and is therefore not susceptible to website or internet availability problem, which can occur with a web-based utility like the PEER Ground Motion Database. Finally, SigmaSpectra has a graphical user interface that allows convenient examination and comparison of ground motions.

Disadvantages

In contrast to the PEER system, a SigmaSpectra user must build, maintain, and update a ground motion database, which can be time-consuming. The algorithm by which SigmaSpectra searches for optimal suites of ground motions can be inefficient, leading to long runtimes for large databases and/or large requested suite sizes.

Baker Codes

A third software tool has been developed by Prof. Jack Baker and colleagues at Stanford University. This tool consists of a suite of Matlab programs that can also select suites of ground motions whose mean matches a target spectrum and scales the suite to match a target standard deviation. The Baker codes use a different approach to that of SigmaSpectra and can complete the selection and scaling process more quickly for a given ground motion database.

The Baker codes come with no ground motion data, although they make use of ground motion meta-data such as that contained in the NGA flatfile assembled by PEER. A user can develop an extended flatfile with ground motion data from other events. The Baker codes have no graphical user interface – data can be plotted in Matlab or written to text files for processing by another graphics program.

Advantages

Like SigmaSpectra, the Baker code is publicly available in source code form, and is resident on the user's computer. The user can build a database that includes ground motions from different sources. The Baker codes are efficient, and can identify an optimum suite of ground motions considerably faster than SigmaSpectra.

Disadvantages

Again, as with SigmaSpectra, the user has responsibility for the ground motion database. The Baker code is written in Matlab, a powerful programming language that is not familiar (or available) to many practicing engineers. Finally, the Baker code does not have a graphical user interface.

Conclusions

The PEER Ground Motion Database system has many attractive capabilities and may eventually represent the best long-term approach for ground motion selection and scaling. However, the limitations of the database itself, i.e., the lack of subduction zone motions, for ground motion hazards in Washington state render it ineffective for short-term use by WSDOT. The length of time that will be required for the database to be expanded to the point at which this system can be used effectively to represent the ground motion hazards that exist in Washington state is not known at this time; given the time required to develop the first version of this system and PEER's current focus on development of GMPEs for the central and eastern United States, it is likely that it will be several years before the PEER utility reaches that state.

The Baker code package is computationally efficient and highly capable, but has no user-friendly interface and would likely require significant effort to master for ground motion selection. Furthermore, the Matlab language in which it is written is not widely available. A graphical user interface could be wrapped around a compiled version of the Baker codes, but development of such an interface would be time-consuming and acquisition of a Matlab compiler expensive.

The SigmaSpectra software tool is capable of performing the type of ground motion selection and scaling that is needed, but does so slowly for large ground motion databases. With an optimized database of moderate size, however, SigmaSpectra can operate with acceptable speed. The current version of SigmaSpectra has good graphics capabilities, but not all of the capabilities that WSDOT would like to see; as a result, some modification of SigmaSpectra would be required.

Based on the preceding review, SigmaSpectra was selected as the platform for ground motion selection and scaling. A number of modifications to the original SigmaSpectra code were made to allow presentation of additional data and processing of ground motion data. In order to allow the modified program to operate efficiently, a ground motion database, termed here the Washington State Ground Motion Database (WSGMDB) was developed. By eliminating ground motions that are not appropriate (or are redundant with respect to other motions) for sites in Washington state, the number of potential ground motion suite combinations can be reduced dramatically. The WSGMDB is a database containing ground motion from multiple sources which have spectral amplitudes and shapes that are generally consistent with AASHTO design spectra at various locations across Washington state.

Chapter 3

Target Spectra

The level of ground shaking used for structural design is generally defined in terms of one or more design response spectra. The design spectra are usually determined from the results of a probabilistic seismic hazard analysis (PSHA) and represent ground motions with a particular mean rate of exceedance, or return period. The use of design spectra with specified return periods allows differences in seismicity to be accounted for in seismic design; for the same return period, the design spectra in areas of high seismicity have higher ordinates than those in areas of low seismicity.

Several different types of spectra can be computed and used for design. If a design is to be based on a goal of elastic structural behavior, the design can be based directly on the design spectrum using modal superposition. Modern seismic design, however, allows some level of inelastic response and increasingly requires the use of nonlinear structural analyses; these, in turn, require ground motion time histories as input. The design spectra then become targets for which ground motions with consistent shapes are sought. The selection and scaling of recorded ground motions to match or exceed some target spectrum is an important part of seismic design. Defining, and understanding, the target spectrum is an important part of that process.

Uniform Hazard Spectrum

PSHAs are commonly performed with spectral acceleration, $S_a(T)$, as a ground motion intensity measure. Performing a suite of PHSAs for spectral acceleration at different structural periods will produce a series of spectra acceleration hazard curves (Figure 3.1a). By selecting a particular mean annual rate of exceedance, a set of $S_a(T)$ values can be obtained and plotted as a function of period (Figure 3.1b). The hazard curves for different periods, T, are performed independently of each other, i.e., without consideration of hazard levels at other periods. The ordinates of the resulting response spectrum all have the same return period, and the spectrum is known as a *uniform hazard spectrum,* or UHS. Uniform hazard spectra can be computed for different return periods.

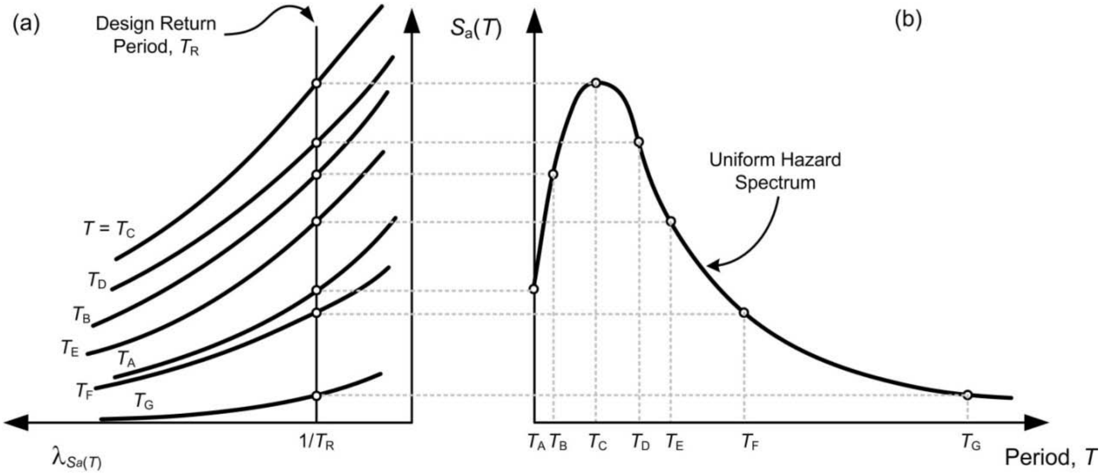


Figure 3.1. Construction of uniform hazard spectrum: (a) Spectral acceleration hazard curves for different structural periods (rotated 90^o from usual presentation), and (b) Spectral accelerations at design return period, T_R, plotted vs. structural period.

Deaggregation of uniform hazard spectra reveals important characteristics that should be recognized when using them for design purposes. Consider the 975-yr return period UHS for Seattle shown in Figure 3.2. Deaggregation of the spectral accelerations at different periods produce the mean magnitude, distance, and ε values shown in Table 3.1. The parameter, e, describes the number of (logarithmic) standard deviations an intensity measure is above the (logarithmic) mean. Note that the values are different – the $S_a(0.1)$ hazard, for example, is associated with lower magnitude, shorter distance events while the $S_a(3.0)$ hazard is coming from higher magnitude, greater distance events. This characteristic of UHS behavior is well recognized – the UHS includes weighted contributions from many different earthquake scenarios (i.e., combinations of magnitude and distance). The result of this characteristic is that, in many cases, no single earthquake event is capable of producing a motion with a response spectrum that matches the entire UHS. Some motions may be consistent with a UHS at lower periods but are weaker at long periods, while others may be consistent at long periods and weaker at short periods. In areas dominated by a single seismic source, the UHS may be consistent with the spectra produced by individual events.

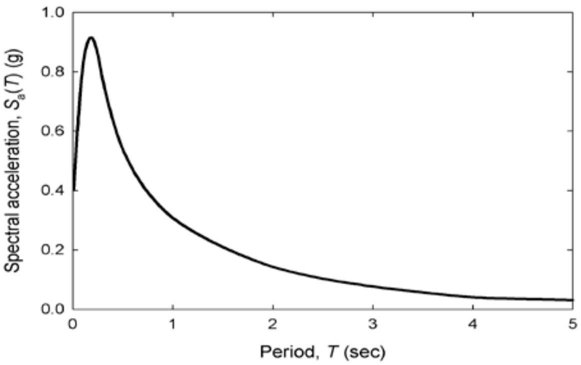


Figure 3.2. 975-yr uniform hazard spectrum for Seattle, WA.

Period, T	$\overline{M}$	$\overline{R}$	$\bar{\epsilon}$
0.0	6.81	43.0	1.11
0.1	6.78	40.5	1.09
0.2	6.94	39.4	1.04
0.3	6.98	43.8	1.05
0.5	7.15	51.8	1.10
1.0	7.49	62.5	1.04
2.0	7.75	75.0	1.00
3.0	7.81	76.0	0.93
4.0	7.97	74.0	0.71
5.0	7.81	65.8	0.74

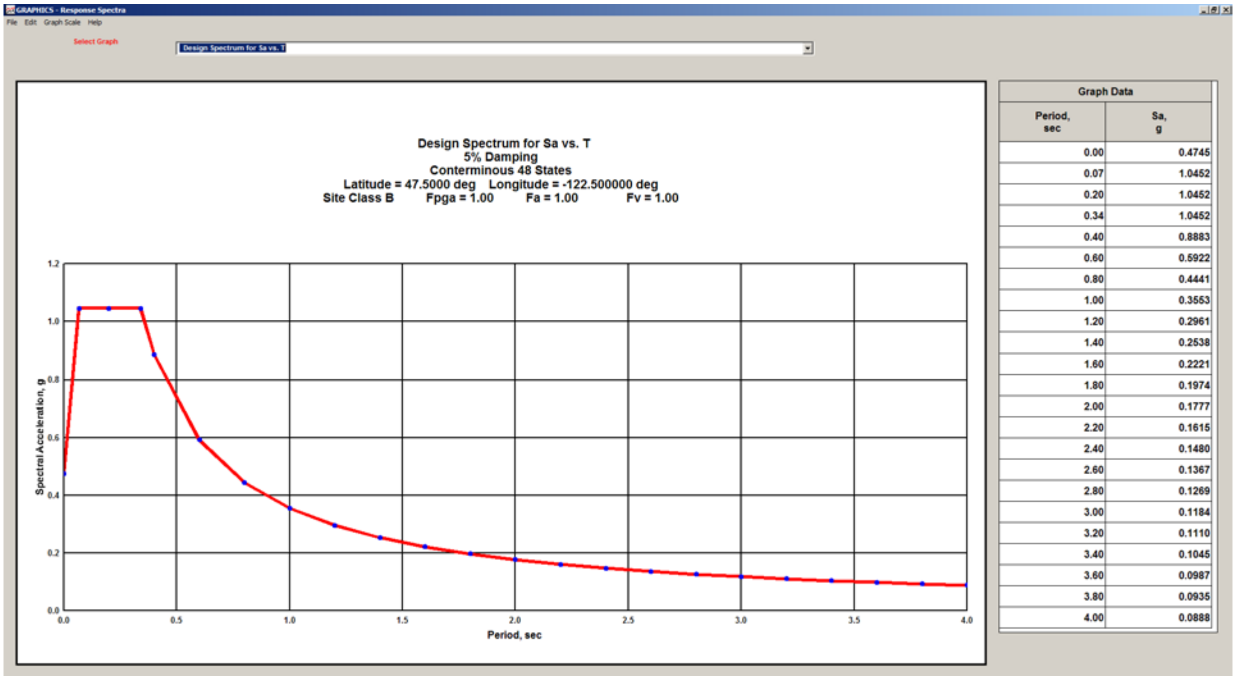
Table 3.1. Mean magnitudes, distances, and epsilon values for 975-yr spectral accelerations at different structural periods.

Uniform hazard spectra are often used as targets for ground motion selection. Most codes specify that a suite of ground motions used for design match (individually or as an ensemble average) or exceed the UHS over some significant period range. The significant period range is typically keyed to the fundamental period of the structure and extends to longer periods (to account for damage-related period lengthening during shaking) and lower periods (to account for higher-mode response). The significant period range (frequently from $0.2T_o$ to $1.5T_o$) may be wide enough, however, that no individual ground motion can reasonably be expected to have a spectrum that matches or exceeds the UHS over that entire range. If that is the case, the motions are generally scaled upward until they meet the code criteria – the motions are then likely to be excessively energetic for the desired hazard level. The scaled motions then represent an actual hazard level that is higher (e.g., corresponds to a longer return period) than intended. A recent study of ground motion selection and modification procedures for buildings (Haselton, 2009) showed that motions selected on the basis of UHS compatibility produced median maximum interstory drift ratios that were biased (high) by a factor of about 1.3.

AASHTO Design Spectra

While site-specific probabilistic seismic hazard analyses may be warranted for major bridge projects or in areas where new understanding of seismic hazards has recently developed, most bridges are designed on the basis of 1,000-yr return period ground motions. The AASHTO LRFD Specifications (2007, 2009) provide guidance for development of design spectra.

The AASHTO spectra are smoothed versions of uniform hazard spectra with standard shapes keyed to spectral accelerations at periods of 0.0, 0.2, and 1.0 sec. The U.S. Geological Survey (USGS) has developed a computer program and database (http://earthquake.usgs.gov/hazards/designmaps/aashtocd.php). The program provides data for developing 1,000-yr spectra for site class B/C (Vs = 760 m/sec), and uses AASHTO amplification factors to account for the effects of local soil conditions. Figure 3.3 illustrates the type of spectrum produced by the AASHTO procedure.



Graph Data	
Period, sec	Sa, g
0.00	0.4745
0.07	1.0452
0.20	1.0452
0.34	1.0452
0.40	0.8883
0.60	0.5922
0.80	0.4441
1.00	0.3553
1.20	0.2961
1.40	0.2538
1.60	0.2221
1.80	0.1974
2.00	0.1777
2.20	0.1615
2.40	0.1480
2.60	0.1367
2.80	0.1269
3.00	0.1184
3.20	0.1110
3.40	0.1045
3.60	0.0987
3.80	0.0935
4.00	0.0888

Figure 3.3 AASHTO design spectrum produced by USGS AASHTO Earthquake Ground Motion Parameters computer program.

Conditional Mean Spectrum

The UHS implicitly assumes that the ground motions from each scenario exceed the median level by a nearly constant amount at all periods – actual earthquake spectra, however, have irregular shapes that cause the amount by which they exceed (or fall below) the median to fluctuate significantly with period. While the ε values for a particular spectrum at two closely-spaced periods are likely to be closely correlated to each other, their correlation decreases when the periods are farther apart. Baker and Cornell (2006a) showed that the correlation coefficient for ε values at two periods, $T_{\min}$ and $T_{\max}$, could be approximated as

$$\rho(T_{\min}, T_{\max}) = 1 - \cos\left[\frac{\pi}{2} - \left(0.359 + 0.163 I_{(T_{\min}<0.189)} \ln\frac{T_{\min}}{0.189}\right)\ln\frac{T_{\max}}{T_{\min}}\right]$$

where $T_{\min}$ and $T_{\max}$ are the lower and higher of the two periods, respectively, and $I_{(T_{\min}<0.189)}$ is an indicator variable equal to 1 if $T_{\min} < 0.189$ and 0 otherwise. Figure 3.4 illustrates the correlation between ε (hence, also $S_a(T)$) values at a period of interest, $T^* = 1.0$, and other periods; the correlation coefficient is 1.0 at the selected period but drops off at periods above and below the selected period. The expected value of ε at periods other than the period of interest is given by

$$\mu_{\varepsilon(T)|\varepsilon(T^*)} = \rho(T, T^*)\varepsilon(T^*)$$

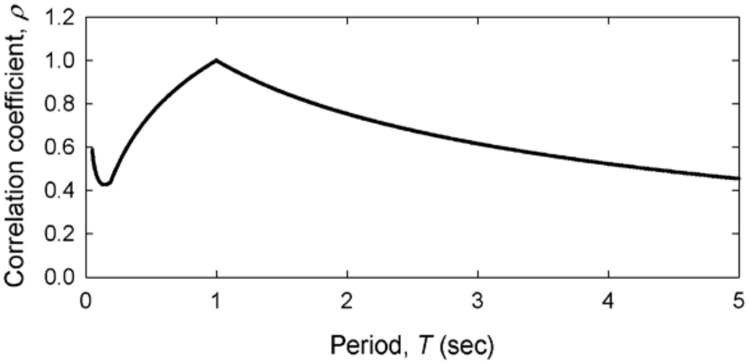


Figure 3.4. Correlation between $S_a(T)$ values at $T = 1.0$ sec and other periods.

So the expected value of the (logarithmic) response spectrum conditional upon $\varepsilon(T^*)$ is given by

$$\mu_{\ln S_a(T)|\ln S_a(T^*)} = \mu_{\ln S_a}(M, R, T) + \mu_{\varepsilon(T)|\varepsilon(T^*)}\sigma_{\ln S_a}(T)$$

The corresponding spectrum is referred to as the *conditional mean spectrum* (CMS). The median spectral accelerations are therefore given by

$$S_a(T) = \exp\left\lfloor \mu_{\ln S_a}(M, R, T) + \rho(T, T^*)\varepsilon(T^*)\sigma_{\ln S_a}(T \right\rfloor$$

The distribution of spectral acceleration at all periods given the value of $S_a(T^*)$ can be obtained from $\mu_{\ln S_a(T)|\ln S_a(T^*)}$ and

$$\sigma_{\ln S_a(T)|\ln S_a(T^*)} = \sigma_{\ln Sa}(T)\sqrt{1 - \rho(T, T^*)^2}$$

Figure 3.5 illustrates the relationship between the CMS and the constant ε (i.e., ε(*T*) = ε(*T**)) scenario spectrum. Note that the CMS falls below the constant ε spectrum at periods other than T*, which reflects the actual behavior of individual ground motions.

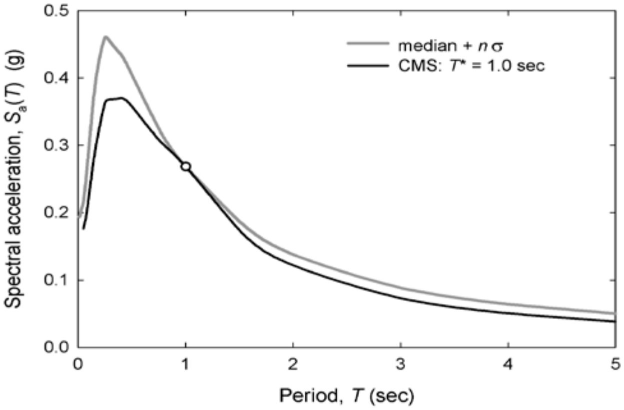


Figure 3.5. Relationship between spectrum with constant ε spectrum and corresponding CMS.

The CMS can be used as a target for ground motion selection, typically with *T** set to the fundamental period of the structure of interest. To cover the range of ground motions that could be expected at a particular site, however, multiple CMS with different *T** values (Figure 3.6) may be required. Ground motions can also be selected to match the distribution of spectral acceleration in order to estimate the distribution of computed response.

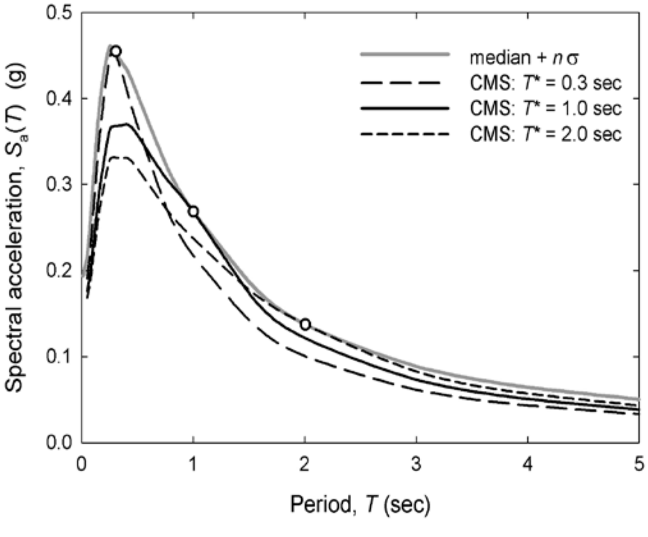


Figure 3.6. Use of multiple CMS to cover broad range of periods.

The CMS provides a more realistic spectrum than the UHS for a given $S_a(T^*)$ in that it has a shape consistent with the shapes of individual ground motions. This shape is based on deaggregation data (M, R, and ε) and ground motion prediction equations, so the shape changes with amplitude in a manner consistent with that observed in actual earthquakes. Haselton (2009) found that motions scaled to fit a CMS produced median maximum interstory drift ratios that were biased (high) by a factor of only 1.01, a value much lower than that (1.3) obtained for motions scaled to fit a UHS. On the other hand, CMS data is less readily available than UHS at this point in time and, given that the CMS changes with amplitude and period of interest, multiple sets of ground motions may be required for design purposes.

While current codes do not specifically address the use of the CMS for design, it may be appropriate for individual projects and may very well become part of future codes. From the standpoint of record selection and scaling, the use of CMS-based target spectra presents no particular difficulties – in fact, better fits are likely to be obtained with a CMS target spectrum than a UHS target spectrum.

Risk-Targeted Ground Motions

In recent years, the concept of risk-targeted ground motions has developed to the point at which it is being used in some current building codes. Risk-targeted ground motions seek to define ground motions that will result in a defined mean annual rate of exceedance of some specified risk level. For buildings, the risk is that of collapse and risk-targeted motions have been developed for a 1% probability of collapse in a 50-yr period, i.e., a collapse return period of 4,975 yrs. The calculations are performed by combining a probabilistic collapse model (one that provides fragility curves describing the probability of collapse conditional upon ground motion intensity) with a ground motion intensity hazard curve. The resulting collapse hazard curve accounts for uncertainty in the ground motion and uncertainty in the hazard given the ground motion.

In effect, risk-targeted ground motions account for the entire hazard curve since the risk is obtained by integrating over all levels of ground motion intensity. Thus, hazard curves with different shapes will produce different risk-targeted ground motions even if the ground motion hazard curves are similar at the return period of interest. Such an approach, which is analogous to the performance-based approach to liquefaction hazard analysis developed by Kramer and Mayfield (2007), allows more uniformity of performance than is obtained by current procedures. Comparing risk-targeted motions with MCE motions from previous codes (e.g., ASCE-07), the risk-targeted motions are significantly (more than 15%) weaker along the Pacific coast of Washington.

Site Effects

Target spectra used for design should account for the effect of local soil conditions on ground surface motions. Site effects can be determined in two primary ways – through the use of amplification factors (which are increasingly incorporated into ground motion prediction equations, or GMPEs) or through site-specific response analyses.

Amplification factors, whether computed separately or contained within GMPEs, are obtained from regression upon empirical data from multiple sites and earthquakes. As a result, an amplification factor is consistent with the average characteristics of the soil profiles in the database from which it was developed. This characteristic can be important in deciding whether or not a site-specific analysis should be performed (it may not be necessary for sites that have average characteristics, e.g., a shear wave velocity profile that increases smoothly with depth), and in deconvolution operations (motions consistent with average velocity profiles should be deconvolved through an average velocity profile rather than a site-specific profile).

When site conditions differ significantly from average conditions, site effects are better accounted for by performing site-specific response analyses. Equivalent linear or nonlinear analyses that take individual shear wave velocity profiles and material characteristics into consideration can be used. When relatively large shear strains (greater than about 1%) are encountered, nonlinear analyses can produce more reasonable results than equivalent linear analyses. When soils capable of generating significant excess porewater pressure are present, nonlinear effective stress analyses should be performed.

Site effects can also influence the type of target spectrum to use in ground motion selection. Because uniform hazard spectra have been criticized as being excessively strong, engineers tend to consider their use as being conservative with the expectation that stronger input motions will lead to stronger seismic response. For a soft soil profile (or strong shaking level), however, motions fit to a uniform hazard spectrum can “overdrive” a soil profile in a site response analysis leading to reduced ground surface motions at some frequencies. If such ground surface motions are used as inputs to a structural analysis, the structure may be subjected to loading that is not consistent with the expected return period.

Discussion

The use of target spectra for selection of earthquake ground motions allows engineers to identify ground motions with amplitudes and frequency contents that are generally consistent with some intended ground motion hazard level. It should be recognized, however, that a response spectrum provides an incomplete representation of an earthquake ground motion – put differently, many different ground motions could have (nearly) the same response spectrum and could induce very different levels of response in structures. For a suite of motions, these differences can lead to dispersion (scatter) in the computed response.

The principal ground motion characteristic that is not well reflected in the response spectrum is duration. Duration is known to affect many aspects of seismic response, particularly for soils. While duration is rarely evaluated explicitly in seismic hazard analyses, it varies with both magnitude and distance and can therefore be at least roughly inferred from the results of deaggregation analyses. With respect to ground motion selection, the likelihood of obtaining motions with appropriate durations is increased by restricting the pool of candidate motions to those with magnitudes and distances that are consistent with those that contribute most strongly to the ground motion hazard at the return period of interest.

Chapter 4

Washington State Ground Motion Database

In order to streamline the ground motion selection and scaling process for transportation structures in Washington, a Washington State Ground Motion Database (WSGMDB) was assembled. The purpose of the WSGMDB was to provide WSDOT with a relatively small database of ground motions with amplitude, frequency content, and duration characteristics similar to those of design ground motions in Washington State. The availability of this Washington-specific database would allow existing software tools for ground motion selection and scaling to be used efficiently in Washington State with only limited modifications.

The ground motions were selected with consideration of AASHTO bridge design code seismic standards, which are based on design response spectra with nominal 975-yr return periods (i.e., with 5% probability of exceedance in a 50-yr period). The selection process also considered consistency with source characteristics such as magnitude and distance. The process by which the WSGMDB motions were identified is described in the following sections.

State-Wide Locations

In order to provide appropriate geographic coverage of the entire state, and to recognize the different levels of seismicity in different parts of the state, a set of 34 cities (Figure 4.1) were identified for consideration of design response spectra. Probabilistic seismic hazard analyses were performed for each of the cities using the USGS National Seismic Hazard Mapping project's Interactive Deaggregations website (https://geohazards.usgs.gov/deaggint/2008/) in order to determine the nature of the earthquake events that contribute most strongly to ground motion hazard at the locations of the various cities. The specific locations, and mean magnitudes and distances for each of the cities are listed in Table 4.1.

Figure 4.1. Locations at which AASHTO design spectra were computed.

Table 4.1. Locations, mean magnitudes, and mean distances at 975-yr hazard level for 34 locations.

City	Location		Mean Deaggregated Values		Group
	Latitude	Longitude	*M*	*R* (km)	
Bellingham	48.80	122.53	6.65	54.20	C
Bremerton	47.48	122.77	7.05	45.20	A
Burlington	48.50	122.33	6.73	52.40	C
Colville	48.88	118.47	6.04	46.40	D
Ephrata	47.32	119.52	6.14	45.90	D
Everett/Paine	47.92	122.28	6.89	33.60	B
Fairchild	47.62	117.65	5.95	34.40	D
Fort Lewis	47.08	122.58	6.91	52.70	B
Goldendale	45.82	120.82	6.62	76.6	D
Hanford	46.57	119.60	6.19	43.30	D
Hoquiam	46.97	123.97	8.30	30.80	A
Kelso/Longview	46.14	122.93	7.78	66.8	C
Long Beach	46.35	124.06	8.6	27.8	A
McChord AFB	47.15	122.48	6.85	52.40	B
Moses Lake	47.20	119.32	6.08	40.20	D
Oak Harbor	48.25	122.68	6.97	42.10	B
Olympia	46.97	122.90	7.21	54.50	B
Omak	48.42	119.53	6.03	32.30	D
Pasco	46.27	119.12	6.12	37.10	D
Port Angeles	48.12	123.50	7.35	35.00	B
Pullman	46.75	117.12	5.96	38.30	D
Quillayute	47.95	124.55	8.55	27.00	A
Renton	47.50	122.22	6.77	36.70	A
Seattle	47.45	122.30	6.81	38.90	A

Shelton	47.25	123.15	7.40	49.60	B
Spokane	47.63	117.53	5.94	33.30	D
Stampede Pas	47.28	121.33	6.45	47.10	C
Tacoma	47.27	122.58	6.89	51.90	B
Toledo	46.48	122.80	7.38	62.10	C
Vancouver	45.63	122.69	7.37	59.7	C
Walla Walla	46.10	118.28	5.96	29.10	D
Wenatchee	47.40	120.20	6.41	64.90	D
Whidbey Island	48.35	122.65	6.87	41.20	B
Yakima	46.57	120.53	6.40	58.50	D

AASHTO design response spectra were then generated for each of the 34 cities using the AASHTO Seismic Design Parameters program (http://earthquake.usgs.gov/hazards/designmaps/aashtocd.php) developed by the U.S. Geological Survey. The Seismic Design Parameters program provides spectral response ordinates at periods ranging from 0 – 4 sec. The design response spectra for all 34 locations are shown in Figure 4.2(a); the spectral ordinates can be seen to cover a wide range due to the different levels of seismicity at the widely spaced locations. Figure 4.2(b) shows the same design spectra normalized with respect to *PGA*– in this form, the different spectral shapes also reflect the different seismicities of the different locations. In particular, the different magnitudes that contribute to seismicity cause significant differences in long-period spectral amplitudes.

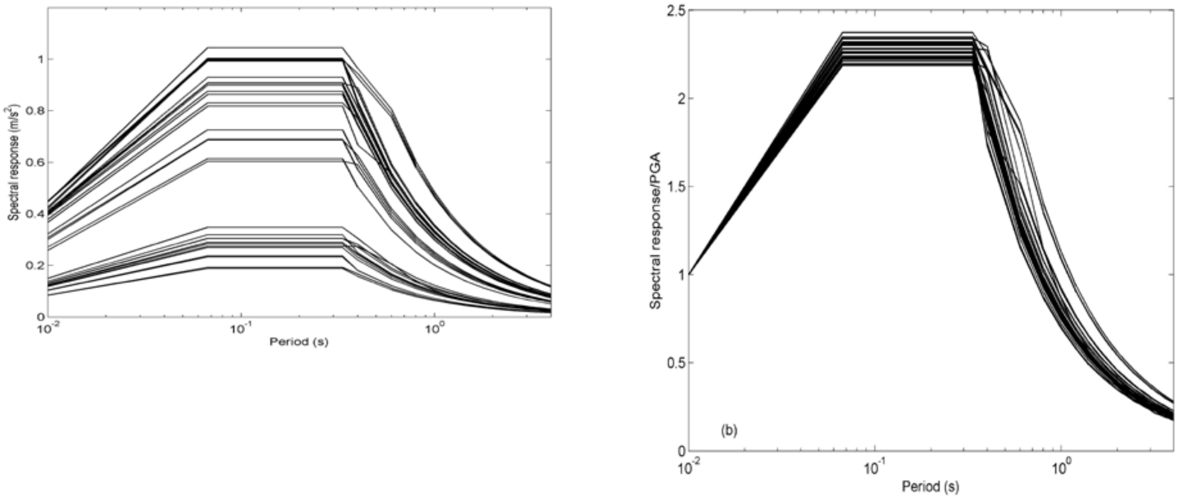


Figure 4.2. (a) Design spectra for 34 locations, and (b) normalized design spectra for 37 locations.

Representative Locations

The design spectra shown in Figure 4.2(a) lend themselves to division into several categories. The spectral acceleration amplitudes, while covering a wide range, tend to fall into a relatively small number of groups, the most obvious being those spectra from locations east of the Cascade mountain range, i.e., from central and eastern Washington, which have maximum spectral acceleration values below 0.40 g. Four groups were defined as having maximum spectral acceleration values in the ranges shown in Table 4.2. Within each of these amplitude-based groups, spectral shapes were examined to identify locations with similar amplitudes but different spectral shapes. Figure 4.3 shows the normalized spectra broken down by amplitude group; all but Group C include spectra with significantly different shapes, particularly, Groups A and D. To cover the ranges of both amplitudes and spectral shapes within the 34 original locations, a subset of 10 sites with significantly different design spectra that encompassed the range of design spectra of the larger group of 34 locations was developed. The 10 spectra are shown, along with the other 24 spectra, in Figure 4.4. The spectra for the representative locations can be seen to span the range of amplitudes and spectral shapes that exist within the larger group of original locations.

Table 4.2. Amplitude groups for selection of design spectra.

Group	Maximum S_a Range
A	$(S_a)_{max} > 0.95$ g
B	0.75 g $< (S_a)_{max} < 0.95$ g
C	0.60 g $< (S_a)_{max} < 0.75$ g
D	$(S_a)_{max} < 0.40$ g

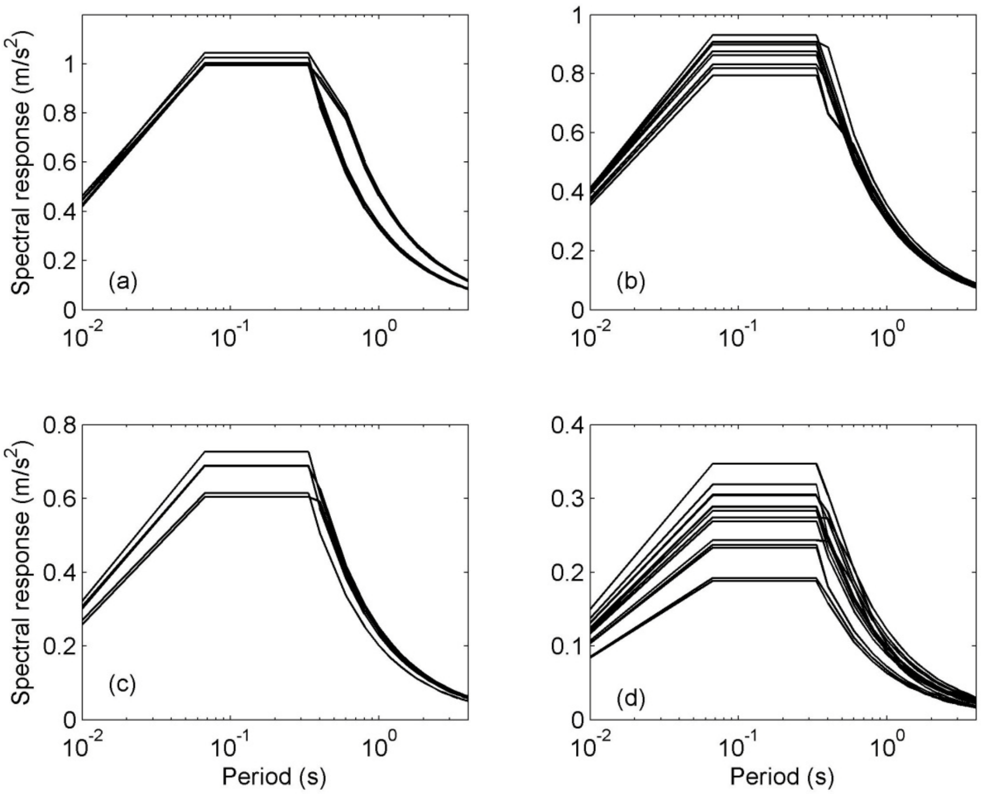


Figure 4.3. Design response spectra for: (a) Group A, (b) Group B, (c) Group C, and (d) Group D.

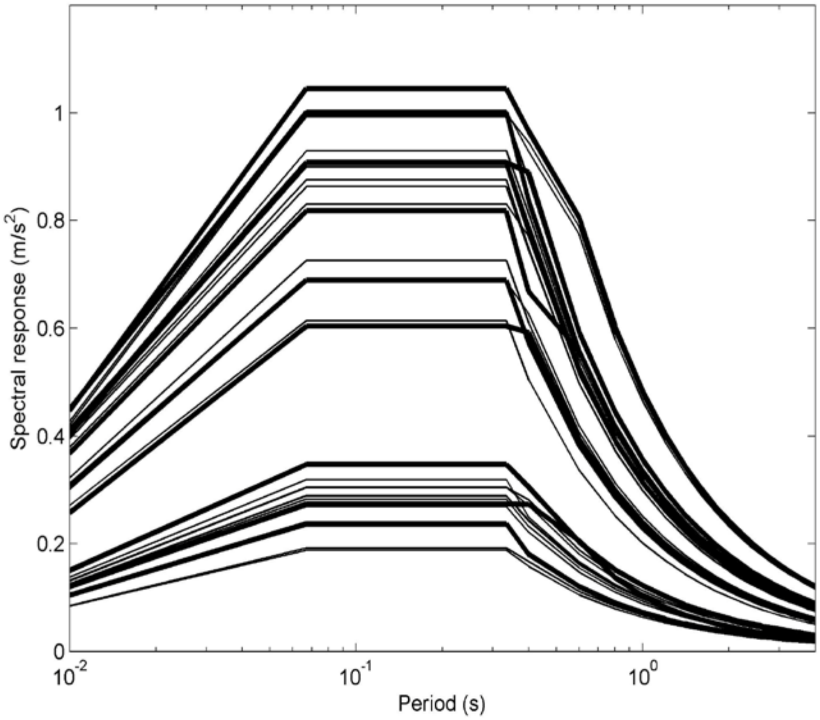


Figure 4.4. Response spectra for all locations with representative locations highlighted.

Ground Motion Selection

The selection of earthquake ground motion records for seismic evaluation and design requires consideration of target spectrum matching by scaled motions, but also of ground motion characteristics not necessarily reflected in response spectra. As a result, three groups of ground motions were identified for inclusion within the WSGMDB: (1) motions that are consistent with the previously described target spectra, (2) long-duration ground motions that would be representative of interplate subduction zone earthquakes, and (3) near-fault ground motions that include directivity pulses representative of those expected at sites near surface faults such as the Seattle fault.

Spectrum-Consistent Motions

A process was developed to identify recorded ground motions that were consistent with the design spectra for the 10 representative locations. A number of ground motion databases are available worldwide, including those listed in Table 4.3. All of the databases in Table 5.3 were queried to obtain records for consideration in assembly of the WSGMDB. The different databases had different search capabilities ranging from those that searched for motions based on compatibility with a target spectrum (e.g., PEER NGA database) to those that could search only on the basis of magnitude, depth, and location (e.g., K-Net database). It should be noted that the motions in the K-Net database have not been processed.

Table 4.3. Sources of strong ground motion records.

Database	URL
PEER NGA	http://peer.berkeley.edu/peer_ground_motion_database/spectras/new
COSMOS	http://db.cosmos-eq.org/scripts/search.plx
CESMD	http://www.strongmotioncenter.org/cgi-bin/ncesmd/search1.pl
K-Net	http://www.k-net.bosai.go.jp/

The databases listed in Table 4.3 were queried to obtain candidate records for inclusion in the WSGMD. Where possible, target spectra consisting of the 10 representative location design spectra were entered and motions that matched those spectra were identified. For databases without target spectrum-matching capabilities, ranges of source parameters (e.g., magnitude, distance, style of faulting) were used to identify motions most likely to be consistent with design spectra. These searches produced a preliminary set of 280 ground motions that were further examined for consistency with the 10 representative location design spectra.

Due to the similarity of some of the design spectra, a number of duplicate records (i.e., records that provided good fits to more than one design spectrum) were obtained. Nevertheless, each representative location design spectrum was well-matched by at least 20 different ground motion records. This led to a final set of 226 motions from which individual records could be selected and scaled to produce good approximations to AASHTO design spectra from within Washington state. The individual motions, and their pertinent characteristics, are summarized in Appendix A.

Long-Duration Motions

Ground motion hazards for structures located near the Pacific coast and for longer-period structures located farther inland, e.g., along the I-5 corridor, are influenced by interplate earthquakes on the Cascadia Subduction Zone. The mean magnitudes for coastal locations such as Hoquiam, Quillayute, and Long Beach, for example, are all considerably greater than 8.0, which indicate strong contributions from large CSZ interplate events. Large-magnitude earthquakes are known to produce long-duration ground motions. Therefore, a suite of long-duration ground motions was developed by searching through several ground motion databases for records from large-magnitude earthquakes. Because large-magnitude events are rare, not many have been well-recorded by modern strong motion instruments; in some cases, the recorded motion database can be supplemented by synthetic ground motions. The recent 2011 Tohoku earthquake, however, was very well recorded by the K-Net and Kik-Net seismographic networks in Japan.

A suite of 241 recorded and 180 simulated long-duration motions was assembled. Many available long-duration ground motions were recorded at distant locations, hence the amplitudes are low enough that excessively large scaling factors would be required to produce reasonable spectral matches; such motions were not included in the final suite of long-duration motions. 138 of the recorded long-duration motions are from the 2011 Tohoku earthquake in Japan – these motions have been baseline-corrected and lightly (0.02 – 50 Hz bandpass) filtered but not instrument-corrected or otherwise processed; the motions should be reviewed, processed as necessary, and approved by a qualified engineering seismologist prior to use. The suite of simulated motions were developed by Dr. Walter Silva of Pacific Engineering and Analysis for a previous WSDOT study (Kramer et al., 1998). The individual long-duration motions and their pertinent characteristics are summarized in Appendix B.

Near-Fault Motions

Ground motions at sites near earthquakes frequently exhibit near-fault characteristics including directivity pulses and fling step. The constructive interference of waves emanating from a rupture front moving toward a site can cause a long-period pulse of motion referred to as a directivity pulse, which is stronger in the fault-normal (FN) direction than the fault-parallel (FP) direction. Fault rupture can also cause a permanent displacement in the slip direction in the near-fault region; this displacement, which is in the FP direction for strike-slip and FN direction for dip-slip events, is referred to as a fling step displacement.

A suite of 182 near-fault motions, all of which have been identified as containing directivity pulses (Baker, 2007) was assembled; the individual motions and their pertinent characteristics are summarized in Appendix C.

Database Organization

The process described in the preceding section produced a total of 829 motions with potential applicability to the design of transportation structures in Washington state. These motions comprise the WSGMDB, and are organized as indicated in Figure 4.5.

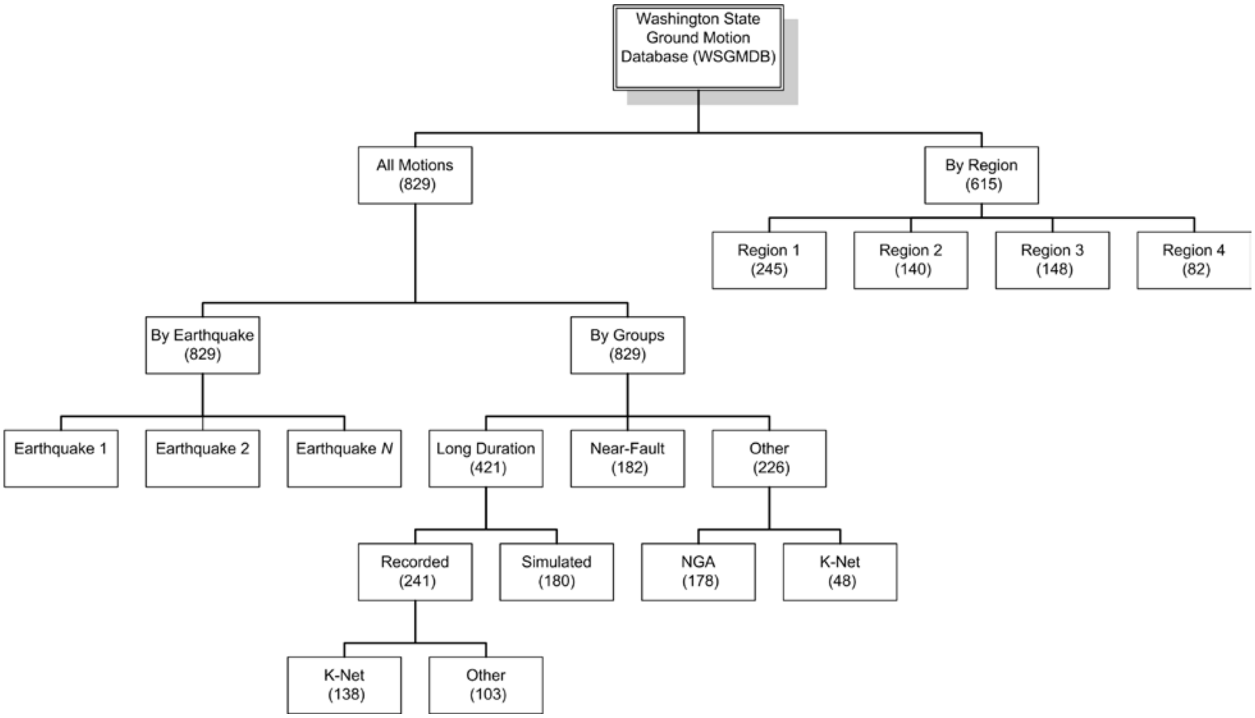


Figure 4.5 Organization of Washington State Ground Motion Database (WSGMDB).

The manner in which the database is organized was developed to simplify the use of SigmaSpectraW. Because the program will use the motions in all subfolders within a user-specified master folder, the database can be optimized for individual sites. If the user wants SigmaSpectraW to consider all 829 motions in the WSGMDB, he/she would simply select the All Motions folder in the path requested on the input screen (Figure 5.1). If the user wanted SigmaSpectraW to consider only the motions within one of the regional databases, he/she would simply select the folder for the path. If the user wanted SigmaSpectraW to consider, for example, all non-K-Net long-duration motions in addition to the regional motions, he/she could copy the Other recorded long-duration motions folder into the regional folder and select the regional folder for the path. In this way, the user is given complete flexibility in selection of the motions to be considered. It is recommended that the user keep a record of the database used in his/her project files.

Earthquake Characteristics

The ground motions in the WSGMDB were produced by 38 different earthquakes with different magnitudes, source-to-site distances, styles of faulting, etc. Table 4.4 presents source data for these earthquakes; these data can be used to assist in the selection of ground motions.

Table 4.4 Characteristics of earthquakes producing ground motions in the WSGMDB.

Earthquake	Year	M_w	Strike (deg)	Dip (deg)	Style of faulting	Hyp. Lat. (deg)	Hyp. Long. (deg)	Hyp. Depth (km)	Surface Rupture
Big Bear-01	1992	6.46	55	85	Strike-slip	34.2100	-116.8300	13.0	N
Cape Mendocino	1992	7.01	350	14	Reverse	40.3338	-124.2294	9.6	N
Chi-Chi, Taiwan	1999	7.62	5	30	Reverse-Oblique	23.8603	120.7995	6.76	Y
Chi-Chi, Taiwan-02	1999	5.90	35	50	Reverse	23.9400	121.0100	8.0	
Chi-Chi, Taiwan-03	1999	6.20	0	10	Reverse	23.8100	120.8500	8.0	
Chi-Chi, Taiwan-04	1999	6.20	330	89	Strike-slip	23.6000	120.8200	18.0	
Chi-Chi, Taiwan-05	1999	6.20	165	70	Reverse	23.8100	121.0800	10.0	
Chi-Chi, Taiwan-06	1999	6.30	5	30	Reverse	23.8700	121.0100	16.0	
Coalinga-01	1983	6.36	137	30	Reverse	36.2330	-120.3100	4.6	N
Coalinga-05	1983	5.77	355	38	Reverse	36.2410	-120.4090	7.4	N
Coalinga-07	1983	5.21	348	38	Reverse	36.2290	-120.3980	8.4	N
Coyote Lake	1979	5.74	336	80	Strike-slip	37.0845	-121.5054	9.6	Y
Denali, Alaska	2002	7.90	296	71	Strike-slip	63.5375	-147.4440	4.86	Y
Erzican, Turkey	1992	6.69	122	63	Strike-slip	39.7050	39.5870	9.0	N
Hector Mine	1999	7.13	331	77	Strike-slip	34.5740	-116.2910	5.0	Y
Imperial Valley-06	1979	6.53	323	80	Strike-slip	32.6435	-115.3088	9.96	Y
Irpinia, Italy-01	1980	6.90	313	60	Normal	40.8059	15.3372	9.5	Y
Irpinia, Italy-02	1980	6.20	124	70	Normal	40.8464	15.3316	7.0	
Kobe, Japan	1995	6.90	230	85	Strike-slip	34.5948	135.0121	17.9	Y
Kocaeli, Turkey	1999	7.51	272	88	Strike-slip	40.7270	29.9900	15.0	Y
Landers	1992	7.28	336	90	Strike-slip	34.2000	-116.4300	7.0	Y
Loma Prieta	1989	6.93	128	70	Reverse-Oblique	37.0407	-121.8829	17.48	N
Mammoth Lakes-06	1980	5.94	22	50	Strike-slip	37.5060	-118.8260	14.0	N
Morgan Hill	1984	6.19	148	90	Strike-slip	37.3060	-121.6950	8.5	Y
N. Palm Springs	1986	6.06	287	46	Reverse-Oblique	34.0000	-116.6117	11.0	N
Norcia, Italy	1979	5.90	341	64	Normal	42.7300	12.9600	6.0	N
Northridge-01	1994	6.69	122	40	Reverse	34.2057	-118.5539	17.5	N
Northwest China-03	1997	6.10	21	45	Normal	39.5557	76.9477	20.0	
San Fernando	1971	6.61	287	50	Reverse	34.4400	-118.4100	13.0	Y
San Salvador	1986	5.80	32	85	Strike-slip	13.6330	-89.2000	10.9	N
Sierra Madre	1991	5.61	242	50	Reverse	34.2591	-118.0010	12.0	N
Sitka, Alaska	1972	7.68	347	90	Strike-slip	56.7700	-135.7840	29.0	N
Superstition Hills-02	1987	6.54	127	90	Strike-slip	33.0222	-115.8314	9.0	Y
Tabas, Iran	1978	7.35	330	25	Reverse	33.2150	57.3230	5.75	Y
Taiwan SMART1(40)	1986	6.32	43	57	Reverse	24.0817	121.5915	15.8	N
Westmorland	1981	5.90	64	90	Strike-slip	33.1000	-115.6200	2.3	N
Whittier Narrows-01	1987	5.99	280	30	Reverse-Oblique	34.0493	-118.0810	14.6	N
Yountville	2000	5.00	150	90	Strike-slip	38.3788	-122.4127	10.12	N

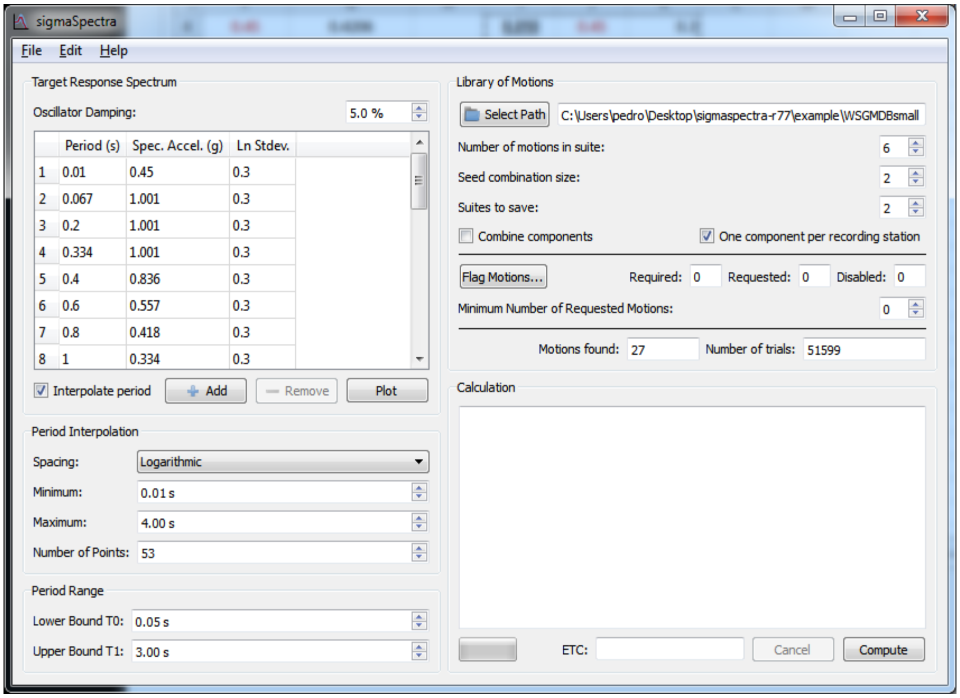
Chapter 5

Ground Motion Selection and Scaling Software Package – SigmaSpectraW

As discussed in Chapter 2, the SigmaSpectra software program (Kottke and Rathje, 2010)was selected as the base platform on which to build a ground motion selection and scaling system that would be appropriate for WSDOT. A number of modifications to the original SigmaSpectra program were made to provide information and utilities requested by WSDOT personnel – the modified program is called SigmaSpectraW. This chapter describes the basic operation of the modified program, drawing heavily on the user manual for the original program.

Input Data

SigmaSpectraW, like the original SigmaSpectra program, opens with a screen (Figure 5.1) that contains four dialog group boxes: target response spectrum, period interpolation, library of motions, and calculations. The data required to run the program is entered by the user in these sections.



Oscillator Damping: 5.0 %

	Period (s)	Spec. Accel. (g)	Ln Stdev.
1	0.01	0.45	0.3
2	0.067	1.001	0.3
3	0.2	1.001	0.3
4	0.334	1.001	0.3
5	0.4	0.836	0.3
6	0.6	0.557	0.3
7	0.8	0.418	0.3
8	1	0.334	0.3

☑ Interpolate period

Spacing: Logarithmic
Minimum: 0.01 s
Maximum: 4.00 s
Number of Points: 53

Lower Bound T0: 0.05 s
Upper Bound T1: 3.00 s

C:\Users\pedro\Desktop\sigmaspectra-r77\example\WSGMDBsmall
Number of motions in suite: 6
Seed combination size: 2
Suites to save: 2
☐ Combine components
☑ One component per recording station
Required: 0
Requested: 0
Disabled: 0
Minimum Number of Requested Motions: 0
Motions found: 27
Number of trials: 51599
ETC:

Figure 5.1 Initial input screen for SigmaSpectraW

Target Response Spectrum

The target response spectrum section allows the user to enter the spectrum against which the selected motions will be compared. The oscillator damping ratio can be specified by the user, but is commonly taken as 5%. The target spectrum data is entered in terms of spectral acceleration values at each of a user-determined set of oscillator periods. The program also requests the (natural) logarithmic standard deviation, $\sigma_{\ln S_a}$, at each period – this value will be zero when the goal is to match a particular uniform hazard or conditional mean spectrum. To account for ground motion variability in motions representing some earthquake scenario, the value of $\sigma_{\ln S_a}$, obtained from an appropriate ground motion prediction equation (GMPE), can be provided so that the program will search for suites of motions that match both a target spectrum and target dispersion. The Plot button allows a plot of the target spectrum to be seen in a separate window. For convenience, the target spectrum data can be imported from a spreadsheet by a simple copy-and-paste operation. It should be noted that the natural variability of actual spectra, along with the limited number of motions in the ground motion database will prevent the standard deviation of the optimum suite of motions from matching the target standard deviation at all periods.

Period Interpolation

If desired, the entered target response spectrum data can be interpolated between to produce a higher-resolution target spectrum against which candidate ground motion spectra can be compared. To interpolate the target spectrum data, the check box within the Target Response Spectrum section must be checked, and the period spacing (linear or logarithmic), minimum and maximum periods, and number of interpolated points (between the minimum and maximum periods) entered. A minimum of 25 points per log cycle of period is recommended for logarithmic interpolation. The interpolation is accomplished using a cubic spline procedure which cannot model sharp corners in target spectra, so this procedure may not be appropriate for some (e.g., code-based) target spectra – it is strongly recommended that the user plot and confirm the validity of the target spectrum prior to beginning the analysis. In some cases, the target spectrum may be better constructed outside of SigmaSpectraW (e.g., using a spreadsheet) at a large number of periods, and then pasted into SigmaSpectraW without interpolation.

Significant Period Range

The original version of SigmaSpectra considered the entire range of periods when identifying optimum suites of motions. SigmaSpectraW allows the user to identify a range of significant periods within which the suites are optimized. The lower and upper bound periods are specified by the user; portions of the spectra outside this significant period range are not considered when evaluating the suite's fit to the target spectrum.

Library of Motions

After the target spectrum has been properly specified, SigmaSpectraW requires the user to set the parameters of the search for optimum suites of motions. The values of these parameters will affect the quality of the identified motions and the speed with which they will be identified. The individual items in the Library of Motions section are described below.

Select Path

The ground motion database from which candidate motions are to be selected is defined by its path. The user should specify a "master" folder within which the candidate motions exist – one folder containing all of the candidate motions may be specified, or the motions may be organized in subfolders within the master folder.

The speed with which the optimum suites of motions will be identified depends strongly on the number of motions in the ground motion database. If speed is important, the selected database should not contain motions that are unlikely to provide a good individual match to the target spectrum. To assist in this process, SigmaSpectraW is accompanied by a ground motion database that is organized into four regional databases which have been preliminarily screened to eliminate motions that do not reasonably fit AASHTO design spectra within those regions. Figure 5.2 shows the boundaries of the four regions; motions can be added to or removed from these regional databases, or they can be subdivided into smaller regions as the user desires. The regions were identified on the basis of spectral amplitudes and shapes. Region 1 represents the coastal region where seismicity is strongly influenced by subduction zone events. Region 2 is approximately the Puget Sound Basin, where intraplate, interplate, and crustal events all influence seismicity. Region 3 is the region south of the Puget Sound Basin where subduction zone events are significant but more distant than in the coastal region. Finally, Region 4 is primarily central and eastern Washington where seismicity is relatively low.

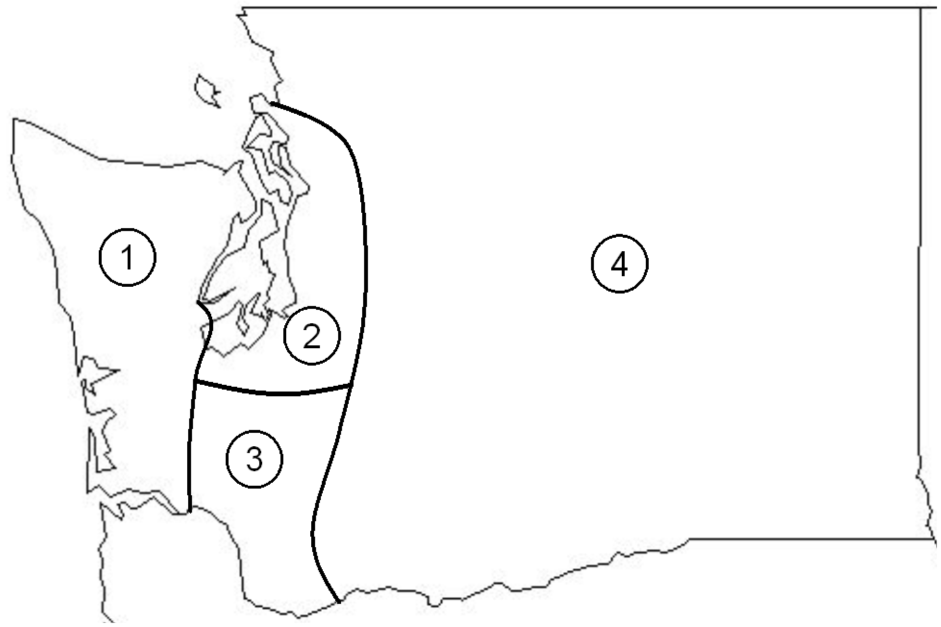


Figure 5.2 Regions used to develop regional ground motion databases.

SigmaSpectraW gives the user complete flexibility in selecting the ground motion database from which the suite of motions will be selected. The user can move individual motion files, or folders containing multiple motions, in or out of the master folder. If a site is on the border between two of the regions shown in Figure 4.2, for example, folders containing the motions from the two regions can be pasted into a new master folder for the purposes of that analysis.

Number of Motions in Suite

SigmaSpectraW is intended to search for a suite of motions whose logarithmic mean is as close as possible to a defined target spectrum. The size of the suite is determined by the user, and generally will be controlled by code requirements – suites of seven motions are commonly specified by code documents. Larger suites require consideration of more combinations of motions and, therefore, have longer runtimes.

Seed Combination Size

To speed up the optimum suite identification process, SigmaSpectraW uses a procedure that avoids checking all possible combinations of motions within the ground motion database. The seed combination size value will affect the rate and accuracy of the identification process; a seed value of 2 has been shown to result in identification of the same motions identified considering all combinations, but to do so in a much shorter period of time.

Suites to Save

The program can save as many suites of motions as the user requests. The various combinations of motions comprising candidate suites are ranked by quality of fit; the requested number of suites will be saved in order of quality of fit.

Combine Components

Individual motions can be considered in the ground motion selection process or pairs of orthogonal horizontal motions can be considered. If the latter is selected, the motions are selected on the basis of their geometric mean spectra – the geometric mean spectral acceleration of a ground motion record with *x*- and *y*-components would be given by $\sqrt{S_{a,x} \cdot S_{a,y}}$.

Flag Motions …

The Flag Motions button will load all ground motions in the specified ground motion database and allow plots of acceleration, velocity, and displacement time histories to be displayed. The name of each file along with a Flag utility is also displayed. Double-clicking the shaded circle in the Flag column will allow the user to specify whether the selected motion is required to be part of each considered suite (Required), barred from being within the considered suites (Disable), or considered without prejudice (Unmarked). The Marked option can be used to define a group of motions from which some user-specified number (specified in the Marked textbox to the right of the Flag Motions button) will be included in each considered suite.

Calculation

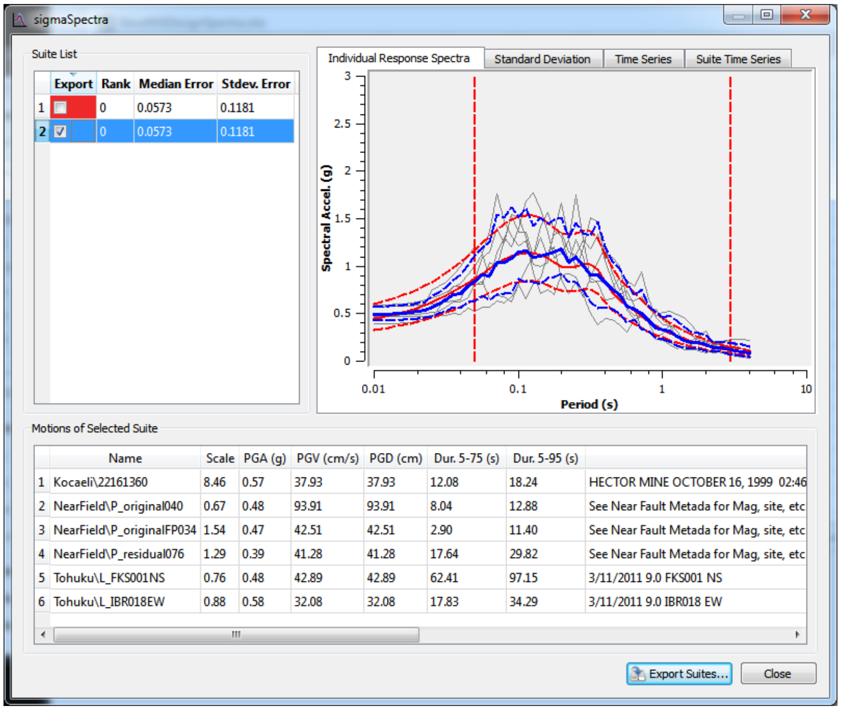
The Calculation section contains a window in which the process of the ground motion selection is displayed and the Compute button that initiates that process.

Output

Upon completion of the suite identification process, SigmaSpectraW will display an output screen that shows a list of the requested suites in order of minimum error, a list of the motions comprising each suite with the individual scaling factors for each motion in the suite, and a series of plotting tabs.

Individual Response Spectra Tab

This tab, which is displayed initially by default, presents plots of the individual response spectra (Figure 5.3) in the highlighted suite. The individual spectra are plotted in gray, along with the median, 84th percentile, and 16th percentile spectra – in red for the target values and in blue for the identified suite. The boundaries of the significant period range are indicated by vertical red dashed lines. This plot allows the user to see the level of consistency between the spectra of the identified motions and the target spectra. Pertinent characteristics of the individual motions, including the scaling factors used for each motion, are displayed in the lower part of the tab.



	Export	Rank	Median Error	Stdev. Error
1	☐	0	0.0573	0.1181
2	☑	0	0.0573	0.1181

	Name	Scale	PGA (g)	PGV (cm/s)	PGD (cm)	Dur. 5-75 (s)	Dur. 5-95 (s)	
1	Kocaeli\22161360	8.46	0.57	37.93	37.93	12.08	18.24	HECTOR MINE OCTOBER 16, 1999 02:46
2	NearField\P_original040	0.67	0.48	93.91	93.91	8.04	12.88	See Near Fault Metada for Mag, site, etc
3	NearField\P_originalFP034	1.54	0.47	42.51	42.51	2.90	11.40	See Near Fault Metada for Mag, site, etc
4	NearField\P_residual076	1.29	0.39	41.28	41.28	17.64	29.82	See Near Fault Metada for Mag, site, etc
5	Tohuku\L_FKS001NS	0.76	0.48	42.89	42.89	62.41	97.15	3/11/2011 9.0 FKS001 NS
6	Tohuku\L_IBR018EW	0.88	0.58	32.08	32.08	17.83	34.29	3/11/2011 9.0 IBR018 EW

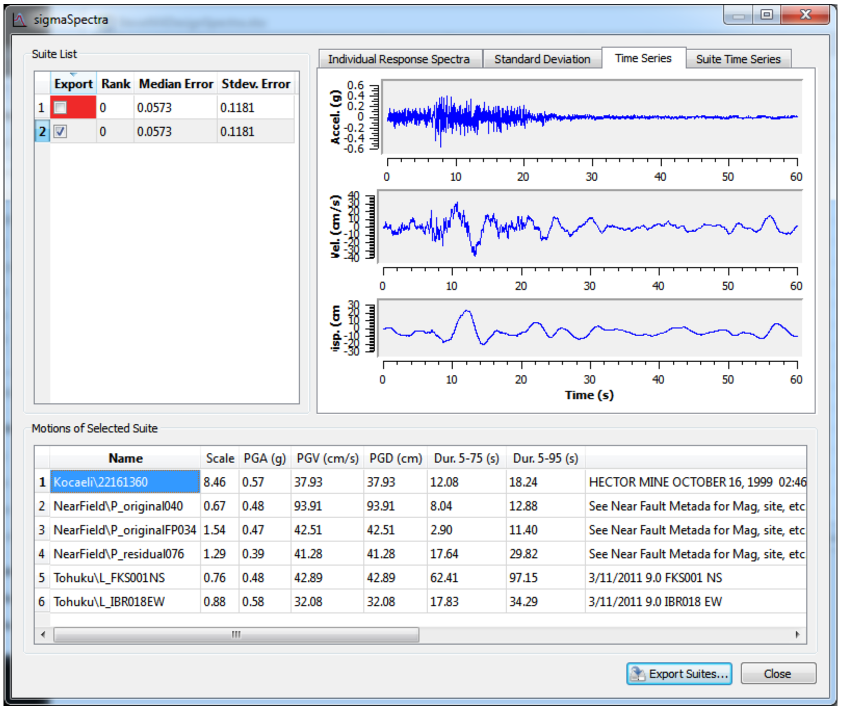
Figure 5.3 Initial output screen for SigmaSpectraW with Individual Response Spectra tab visible.

Standard Deviation Tab

The standard deviation tab simply shows the standard deviation of the identified spectra plotted as a function of period.

Time Series Tab

The characteristics of individual motions are easily viewed using the Time Series tab. Clicking once on an individual motion in the lower part of the tab will produce plots of acceleration, velocity, and displacement as functions of time. These plots (Figure 5.4) are useful for visualizing ground motion characteristics and confirming baseline correction.



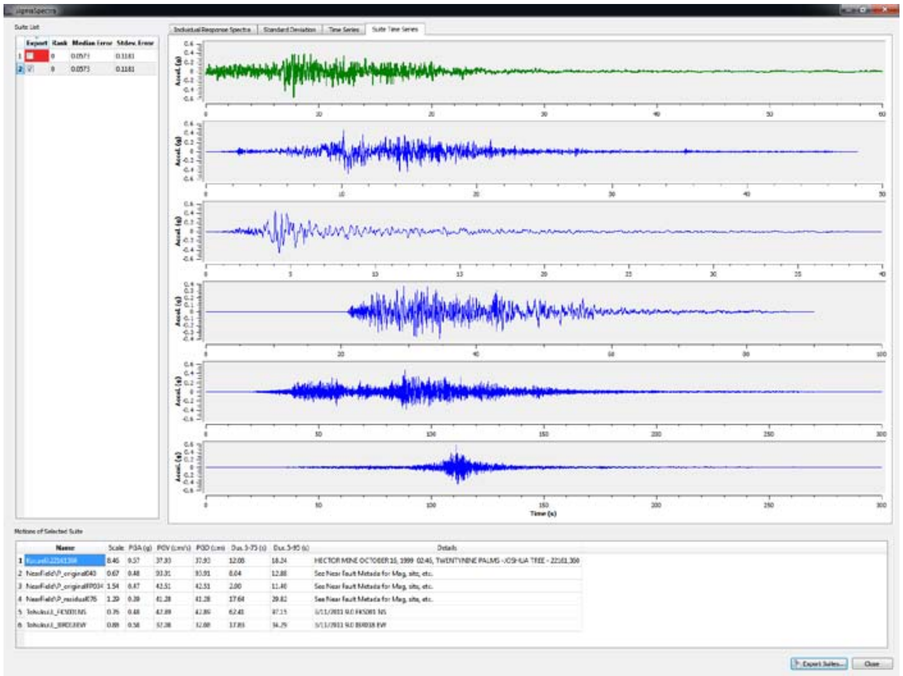
	Export	Rank	Median Error	Stdev. Error
1	☐	0	0.0573	0.1181
2	☑	0	0.0573	0.1181

	Name	Scale	PGA (g)	PGV (cm/s)	PGD (cm)	Dur. 5-75 (s)	Dur. 5-95 (s)	
1	Kocaeli\22161360	8.46	0.57	37.93	37.93	12.08	18.24	HECTOR MINE OCTOBER 16, 1999 02:46
2	NearField\P_original040	0.67	0.48	93.91	93.91	8.04	12.88	See Near Fault Metada for Mag, site, etc
3	NearField\P_originalFP034	1.54	0.47	42.51	42.51	2.90	11.40	See Near Fault Metada for Mag, site, etc
4	NearField\P_residual076	1.29	0.39	41.28	41.28	17.64	29.82	See Near Fault Metada for Mag, site, etc
5	Tohuku\L_FKS001NS	0.76	0.48	42.89	42.89	62.41	97.15	3/11/2011 9.0 FKS001 NS
6	Tohuku\L_IBR018EW	0.88	0.58	32.08	32.08	17.83	34.29	3/11/2011 9.0 IBR018 EW

Figure 5.4 Output screen for SigmaSpectraW with Time Series tab visible.

Suite Time Series Tab

It is often useful to compare ground motion time histories with each other. The Suite Time Histories tab (Figure 5.5) allows up to seven motions to be plotted simultaneously. Note that the motions are individually scaled so the acceleration and time scales may be different.



	Export	Rank	Median Error	Stdev Error
1	☐	0	0.0571	0.1181
2	☑	0	0.0573	0.1181

	Name	Scale	PGA (g)	PGV (cm/s)	PGD (cm)	Dur. 5-75 (s)	Dur. 5-95 (s)	Details
1	[illegible]	0.46	0.57	37.93	37.93	12.08	18.24	HECTOR MINE OCTOBER 16, 1999 02:46, TWENTYNINE PALMS - JOSHUA TREE - 22161.360
2	NearField\P_original043	0.67	0.48	93.31	93.91	8.04	12.88	See Near Fault Metada for Mag, site, etc.
3	NearField\P_originalFP034	1.54	0.47	42.51	42.51	2.00	11.40	See Near Fault Metada for Mag, site, etc.
4	NearField\P_residualK76	1.20	0.39	41.28	41.28	17.64	29.82	See Near Fault Metada for Mag, site, etc.
5	TohokuJ_FKS001NS	0.75	0.48	47.89	42.89	62.43	87.15	3/11/2011 9.0 FKS001 NS
6	TohokuJ_IBR018EW	0.89	0.58	57.28	32.88	17.83	34.29	3/11/2011 9.0 IBR018 EW

Figure 5.5 Outputscreen for SigmaSpectraW with Suite Time Series tab visible.

Exporting Data

The scaled earthquake motions can be exported for use by other programs. Suites can be selected for export using the check boxes in the first column of the Suite List on the main output window. Suites that have been marked for export are exported by clicking the Export Suites button in the lower right portion of the output window. The suite can be exported in a variety of formats. The most general use is the comma-separated values (CSV) format as it also includes the response spectra of each ground motion in the suite. Information for each suite is exported to a different file name, the prefix of which can be specified. If the “Include Time Histories” checkbox is checked, each scaled ground motion time history is saved to an independent file; the name of which is established using the prefix, suite number, and motion number (e.g. suite1-m1.eq). If the “CSV” radio button is checked, the format style specified in the “General earthquake file format” group box is used. This group box allows the specification of the number of header lines at the beginning of the file, the number of columns of acceleration data, the field width (total number of characters including decimal points and +/- signs) of each acceleration value, and the number of digits to the right of the decimal point for each acceleration value. If the “NGA” or “Shake200” radio buttons are checked this format option is not enabled since for these cases the formats are fixed and hardwired in the code.

Comments on Use of Program

SigmaSpectraW should be viewed as a tool to be used in the process of selecting ground motions for use in seismic analysis and design. It is not, and should not be viewed as, a complete, turnkey solution to the ground motion selection and modification process. SigmaSpectraW will assist an engineer or seismologist in selecting suites of spectrum-consistent motions from a database – it is the obligation of the user, however, to ensure that the database contains appropriate motions and that the suites of motions identified by SigmaSpectraW are appropriate for the specific site of interest. This means that the user should be familiar with basic concepts of seismology and earthquake engineering, and should have some experience in dealing with earthquake motions.

SigmaSpectraW should be used in an iterative manner. Using ground motion databases such as those within the WSGMDB without any user interaction can result in suites of ground motions populated by motions that fit the target spectrum well, but do not necessarily represent ground motion hazards well. The databases cover wide areas within which ground motion hazards may vary significantly – fine-tuning the database to the specific site of interest may be required to obtain an optimal suite of ground motions. A series of potential problems and with suggested solutions are described in Table 5.1.

Table 5.1 Potential problems and solutions with ground motion selection process.

Problem	Effect	Solution
Suite contains too many motions from same earthquake	Motions have same source effects (magnitude, style of faulting, rupture pattern, etc.). Correlation of motions may underestimate variability in computed response.	Check database in advance to ensure that motions from variety of events are available; mark motions so that number from a particular event is limited.
Too many motions from one “type” of earthquake	Some sites have hazard contributions from different sources (e.g. crustal, interplate, and intraplate events). Suite of motions should reflect range of source types contributing to ground motion hazards at site.	Examine disaggregation data for site of interest and identify contributions of individual sources prior to SigmaSpectraW analysis. Examine results and compare distribution of selected motions with distribution of hazard.
Too few motions from a particular “type” of earthquake	Important ground motion hazard characteristics (e.g., near-fault directivity pulse) may not be present	Make sure motions with desired characteristics (e.g. near-fault pulse motions) are in database,

	within selected suite. Some structures may be sensitive to these characteristics – sensitivity will not be seen in computed response if not included in selected suite of motions.	and mark in advance so that desired numbers are selected.
Suite contains unrepresentative motions	The program selects motions based on response spectra, so other characteristics are not accounted for. A motion from an earthquake with a magnitude far above (or below) the range of magnitudes controlling the hazard may have a shape similar to that of the target spectrum and be selected, even though its duration would be longer (or shorter) than expected for the hazard.	Check database in advance to eliminate motions from earthquakes with unreasonably high or low magnitudes; mark motions in database so that motions from some events are not considered. After running the program, check the selected motions, eliminate inappropriate motions, and repeat the selection process.
Suite contains outlier motions	The program may produce a suite of motions whose mean matches the target spectrum very well, but which does so by including one or two motions whose individual spectra fall far above (or below) the mean at some frequencies. Analyses using these motions may overpredict variability in response and, if significantly nonlinear response develops, overpredict mean response.	Request multiple suites and examine results closely for outliers – if found, look at other suites. If found in all requested suites, eliminate from database and repeat selection process. Fit of mean spectrum may be somewhat worse, but reduction in dispersion can make up for it.

With careful use by an experienced and attentive user, SigmaSpectraW should greatly speed the process of identifying ground motions for use in the seismic design and evaluation of transportation structures in Washington state.

Chapter 6

Summary

As seismic design continues to move toward the adoption of performance-based concepts, the need to predict the response of soil-foundation-structure systems to strong earthquake shaking requires the increased use of nonlinear analysis. Because nonlinear analyses operate in the time domain, they require ground motion time histories as inputs. As a result, tools and procedures for the identification and selection of appropriate ground motion time histories are required. A great deal of recent research has addressed the general topic of ground motion selection and modification, and several tools that aid in this process have been developed. This report describes the customization of an existing tool and development of an accompanying ground motion database that can aid in the seismic design of structures in Washington state.

The Washington State Department of Transportation expressed the desire for a ground motion selection and scaling tool that could be used efficiently and effectively for sites within the state. A review of available ground motion processing software and evaluation of their relative strengths and weaknesses for WSDOT's purposes was conducted. Three primary tools were identified – the PEER Ground Motion Database website, the computer program, SigmaSpectra (Kottke and Rathje, 2010), and a suite of Matlab programs developed by Prof. Jack Baker and his students at Stanford University. The PEER tool is limited to the use of ground motions in the PEER NGA database, which does not currently include subduction zone motions which are very important in Washington state. The Baker tools are written in Matlab, a powerful language that is not readily available to WSDOT engineers. SigmaSpectra is a public domain program for which source code is available and for which custom ground motion databases can be developed; SigmaSpectra was identified as the most appropriate solution for this project.

Ground motion selection is generally performed in a manner that seeks consistency with design ground motion response spectra. The design spectrum, which usually results from a probabilistic seismic hazard analysis and therefore is associated with a particular return period, is used as a target spectrum against which the response spectra of individual candidate motions are compared. Suite of motions, typically 3 or 7 in number, whose ensemble average is consistent with the target spectrum, are sought. Target spectra are often uniform hazard spectra or, as in the case of the AASHTO design spectra, simplified versions of uniform hazard spectra. Uniform hazard spectra are response spectra for which all spectral ordinates have the same mean annual rate of exceedance, or return period. The ordinates at all oscillator periods are computed independently, which implies that they are considered to be statistically independent. This characteristic can lead to situations where different parts of a uniform hazard spectrum are controlled by different types of seismic events, and in which no individual event is capable of producing the uniform hazard spectrum. Conditional mean spectra were developed to better describe expected earthquake ground motions in such situations. Conditional mean spectra, however, are tied to particular oscillator periods so that 2-3 conditional mean spectra may be required to adequately characterize ground shaking hazards at a particular site. Finally, risk-targeted ground motions make use of integrated ground motion-response-damage relationships to produce targets associated with a specified risk of a particular level of damage (e.g., collapse).

A software tool was customized and a ground motion database developed for use by WSDOT and other organizations involved in seismic design of structures in Washington state. The software tool is an extended version of the computer program, SigmaSpectra, developed at the University of Texas (Kottke and Rathje, 2010). Modifications include provision of the ability to identify a range of oscillator periods over which suites of motions are optimized, additional graphical capabilities that allow the characteristics of ground motions to be more readily viewed, and the ability to export scaled time histories in different user-selected formats. The modified software tool is referred to as SigmaSpectraW.

Because the speed of the algorithm used to identify optimal suites of ground motion time histories drops quickly with increasing numbers of candidate motions, a ground motion database tailored to seismic hazards in Washington state was developed. AASHTO design spectra were computed for 34 cities spread across Washington state. The spectra were grouped into similar levels and spectral shapes, and sets of motions generally consistent with each group were identified. Sets of near-fault and long-duration motions were also assembled. A total of 829 motions, each of which is applicable to ground motion hazards at some location in Washington state, were assembled; this smaller, customized database allows SigmaSpectraW to obtain high-quality suites of design ground motions much more efficiently than would be possible with a much larger ground motion database.

The SigmaSpectraW tool and its accompanying database will allow WSDOT engineers to identify suites of ground motions useful for seismic design calculations at sites throughout Washington state.

References

Baker J.W. (2007). “Quantitative classification of near-fault ground motions using wavelet analysis,”*Bulletin of the Seismological Society of America*, 97 (5), 1486-1501.

Kottke, A.R. and Rathje, E.M. (2010).*Technical Manual for SigmaSpectra*, http://nees.org/resources/1491.

Kramer, S.L., Silva, W.J., and Baska, D.A. (1998). “Ground motions due to large magnitude subduction zone earthquakes,” *Research Report*, Project T9903, Task 67, Washington State Transportation Center, 76 pp.

Kramer, S.L. and Mayfield, R.T. (2007). “The return period of liquefaction,” *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 133, No. 7, pp. 1-12.

APPENDICES

Appendix A. Metadata for Spectrum-Consistent Motions

File names		Event	Recording Station	Date	Magnitude	R_{rup} (km)	R_{ep} (km)
BigBear1/RCD180.AT2	BigBear1/SVP090.AT2	Big Bear-01	Rancho Cucamonga - Deer Can	1992	6.5	59.4	-
BigBear1/SVP360.AT2	BigBear1/WBR090.AT2	Big Bear-01	Silent Valley - Poppet Flat	1992	6.5	35.2	-
BigBear1/WBR360.AT2	BigBear1/ACI000.AT2	Big Bear-01	Winchester Bergman Ran	1992	6.5	59.4	-
CapeMendocino/PET090.AT2	CapeMendocino/LCN260.AT2	Cape Mendocino	Petrolia	1992	7.0	8.2	-
Chi-Chi/CHY042-E.AT2	Chi-Chi/CHY042-N.AT2	Chi-Chi, Taiwan	CHY042	1999	7.6	28.2	-
Chi-Chi/CHY086-E.AT2	Chi-Chi/CHY086-N.AT2	Chi-Chi, Taiwan	CHY086	1999	7.6	28.4	-
Chi-Chi/CHY102-E.AT2	Chi-Chi/CHY102-N.AT2	Chi-Chi, Taiwan	CHY102	1999	7.6	37.7	-
Chi-Chi/HWA003-N.AT2	Chi-Chi/HWA003-W.AT2	Chi-Chi, Taiwan	HWA003	1999	7.6	56.1	-
Chi-Chi/HWA057-E.AT2	Chi-Chi/HWA057-N.AT2	Chi-Chi, Taiwan	HWA057	1999	7.6	50.6	-
Chi-Chi/ILA063-N.AT2	Chi-Chi/ILA063-W.AT2	Chi-Chi, Taiwan	ILA063	1999	7.6	61.1	-
Chi-Chi/ILA067-E.AT2	Chi-Chi/ILA067-N.AT2	Chi-Chi, Taiwan	ILA067	1999	7.6	38.8	-
Chi-Chi/KAU050-E.AT2	Chi-Chi/KAU050-N.AT2	Chi-Chi, Taiwan	KAU050	1999	7.6	40.5	-
Chi-Chi/TCU085-E.AT2	Chi-Chi/TCU085-N.AT2	Chi-Chi, Taiwan	TCU085	1999	7.6	58.1	-
Chi-Chi/TTN025-E.AT2	Chi-Chi/TTN025-V.AT2	Chi-Chi, Taiwan	TTN040	1999	7.6	48.3	-
Chi-Chi/TTN040-N.AT2	Chi-Chi/TTN040-W.AT2	Chi-Chi, Taiwan	TTN042	1999	7.6	65.2	-
Chi-Chi/TTN042-N.AT2	Chi-Chi/TTN042-W.AT2	Chi-Chi, Taiwan	TTN051	1999	7.6	36.7	-
Chi-Chi2/TCU045-E.AT2	Chi-Chi2/TCU045-N.AT2	Chi-Chi, Taiwan-02	TCU045	1999	5.9	59.4	-
Chi-Chi3/TCU102-E.AT2	Chi-Chi3/TCU102-N.AT2	Chi-Chi, Taiwan-03	TCU102	1999	6.2	45.4	-
Chi-Chi4/TTN040-N.AT2	Chi-Chi4/TTN040-W.AT2	Chi-Chi, Taiwan-04	TTN040	1999	6.2	50.8	-
Chi-Chi5/HWA003-N.AT2	Chi-Chi5/HWA003-W.AT2	Chi-Chi, Taiwan-05	HWA003	1999	6.2	50.4	-
Chi-Chi5/TCU102-E.AT2	Chi-Chi5/TCU102-N.AT2	Chi-Chi, Taiwan-05	TCU102	1999	6.2	52.8	-
Chi-Chi6/HWA003-N.AT2	Chi-Chi6/HWA003-W.AT2	Chi-Chi, Taiwan-06	HWA003	1999	6.3	56.0	-
Chi-Chi6/TCU102-E.AT2	Chi-Chi6/TCU102-N.AT2	Chi-Chi, Taiwan-06	TCU102	1999	6.3	35.5	-
Coalinga1/H-SCN045.AT2	Coalinga1/H-SCN315.AT2	Coalinga-01	Slack Canyon	1983	6.4	27.5	-
Denali/22161090.AT2	Denali/22161360.AT2	Denali, Alaska	Carlo (temp)	2002	7.9	50.9	-

Denali/5595-090.AT2	Denali/5596-090.AT2	Denali, Alaska	R109 (temp)	2002	7.9	43.0	-
Geiyo/OIT013EW.AT2	Geiyo/OIT013NS.AT2	Geiyo	OIT013	2001	6.4	-	154.0
Geiyo/YMG019EW.AT2	Geiyo/YMG019NS.AT2	Geiyo	YMG019	2001	6.4	-	62.5
HectorMine/12647090.AT2	HectorMine/12647180.AT2	Hector Mine	Twentynine Palms	1999	7.1	42.1	-
HectorMine/22T04090.AT2	HectorMine/22T04180.AT2	Hector Mine	Hector	1999	7.1	11.7	-
HectorMine/HEC000.AT2	HectorMine/HEC090.AT2	Hector Mine	Joshua Tree N.M. - Keys View	1999	7.1	50.4	-
HectorMine/vquez000.AT2	HectorMine/vquez090.AT2	Hector Mine	Heart Bar State Park	1999	7.1	61.2	-
Hokkaido/HKD038EW.AT2	Hokkaido/HKD038NS.AT2	Hokkaido	HKD038	2003	8.0	-	197.6
Irpinia1/A-ARI000.AT2	Irpinia1/A-ARI270.AT2	Irpinia, Italy-01	Arienzo	1980	6.9	52.9	-
Irpinia1/A-AUL000.AT2	Irpinia1/A-AUL270.AT2	Irpinia, Italy-01	Auletta	1980	6.9	9.6	-
Irpinia1/A-BAG000.AT2	Irpinia1/A-BAG270.AT2	Irpinia, Italy-01	Bagnoli Irpinio	1980	6.9	8.2	-
Irpinia1/A-BIS000.AT2	Irpinia1/A-BIS270.AT2	Irpinia, Italy-01	Bisaccia	1980	6.9	21.3	-
Irpinia2/B-AUL000.AT2	Irpinia2/B-AUL270.AT2	Irpinia, Italy-02	Auletta	1980	6.2	29.9	-
Irpinia2/B-STU000.AT2	Irpinia2/B-STU270.AT2	Irpinia, Italy-02	Sturno	1980	6.2	20.4	-
Iwaki/MYG011EW.AT2	Iwaki/MYG011NS.AT2	Iwaki	MYG011	1998	5.4	-	157.0
Iwate1/MYG011EW.AT2	Iwate1/MYG011NS.AT2	Iwate1	MYG011	2001	6.4	-	124.2
Iwate2/MYG011EW.AT2	Iwate2/MYG011NS.AT2	Iwate2	MYG011	2008	6.8	-	159.1
JapanCoast/MYG011EW.AT2	JapanCoast/MYG011NS.AT2	JapanCoast	MYG011	1999	5.5	-	81.3
JapanCoast2/MYG011EW.AT2	JapanCoast2/MYG011NS.AT2	JapanCoast2	MYG011	2000	5.0	-	34.2
JapanCoast3/MYG011EW.AT2	JapanCoast3/MYG011NS.AT2	JapanCoast3	MYG011	2001	5.4	-	68.9
JapanCoast4/MYG011EW.AT2	JapanCoast4/MYG011NS.AT2	JapanCoast4	MYG011	2002	6.1	-	86.4
JapanCoast5/MYG011EW.AT2	JapanCoast5/MYG011NS.AT2	JapanCoast5	MYG011	2003	6.2	-	31.5
JapanCoast6/MYG011EW.AT2	JapanCoast6/MYG011NS.AT2	JapanCoast6	MYG011	2010	5.5	-	77.0
Kagoshima/KMM014EW.AT2	Kagoshima/KMM014NS.AT2	Kagoshima	KMM014	1997	6.2	-	70.1
Kocaeli/IZT090.AT2	Kocaeli/IZT180.AT2	Kocaeli, Turkey	Izmit	1999	7.5	7.2	-
Kocaeli/MSK000.AT2	Kocaeli/MSK090.AT2	Kocaeli, Turkey	Maslak	1999	7.5	55.3	-
KyushuM5.5/OIT013EW.AT2	KyushuM5.5/OIT013NS.AT2	KyushuM5.5	OIT013	2006	5.5	-	71.0
KyushuM5.7/OIT013EW.AT2	KyushuM5.7/OIT013NS.AT2	KyushuM5.7	OIT013	2002	5.7	-	76.0
KyushuM6.3/KMM014EW.AT2	KyushuM6.3/KMM014NS.AT2	KyushuM6.3	KMM014	1997	6.3	-	63.1
KyushuM6.6/OIT013EW.AT2	KyushuM6.6/OIT013NS.AT2	KyushuM6.6	OIT013	1996	6.6	-	144.4

Landers/29P090.AT2	Landers/RCD090.AT2	Landers	Twentynine Palms	1992	7.3	41.4	-
Landers/LCN345.AT2	Landers/SIL000.AT2	Landers	Lucerne	1992	7.3	2.2	-
Landers/SIL090.AT2	Landers/29P000.AT2	Landers	Silent Valley - Poppet Flat	1992	7.3	50.9	-
LomaPrieta/CH09090.AT2	LomaPrieta/MCH000.AT2	Loma Prieta	Lower Crystal Springs Dam dwnst	1989	6.9	48.4	-
LomaPrieta/G01000.AT2	LomaPrieta/G01090.AT2	Loma Prieta	Gilroy Array #1	1989	6.9	9.6	-
LomaPrieta/GIL067.AT2	LomaPrieta/GIL337.AT2	Loma Prieta	Gilroy - Gavilan Coll.	1989	6.9	10.0	-
LomaPrieta/LOB090.AT2	LomaPrieta/PET000.AT2	Loma Prieta	UCSC Lick Observatory	1989	6.9	18.4	-
LomaPrieta/MCH090.AT2	LomaPrieta/PJH045.AT2	Loma Prieta	Monterey City Hall	1989	6.9	44.4	-
LomaPrieta/PHT360.AT2	LomaPrieta/RIN000.AT2	Loma Prieta	SF - Pacific Heights	1989	6.9	76.0	-
LomaPrieta/PJH315.AT2	LomaPrieta/SG3261.AT2	Loma Prieta	Piedmont Jr High	1989	6.9	73.0	-
LomaPrieta/RIN090.AT2	LomaPrieta/TLH000.AT2	Loma Prieta	SF - Rincon Hill	1989	6.9	74.1	-
LomaPrieta/SG3351.AT2	LomaPrieta/PHT270.AT2	Loma Prieta	SAGO South - Surface	1989	6.9	34.3	-
LomaPrieta/SSF205.AT2	LomaPrieta/UC2000.AT2	Loma Prieta	So. San Francisco, Sierra Pt.	1989	6.9	63.1	-
LomaPrieta/TLH090.AT2	LomaPrieta/SSF115.AT2	Loma Prieta	SF - Telegraph Hill	1989	6.9	76.5	-
LomaPrieta/UC2090.AT2	LomaPrieta/LOB000.AT2	Loma Prieta	UCSC	1989	6.9	18.5	-
MorganHill/LOB050.AT2	MorganHill/LOB320.AT2	Morgan Hill	UCSC Lick Observatory	1984	6.2	45.5	-
MtFuji/OIT013EW.AT2	MtFuji/OIT013NS.AT2	MtFuji	OIT013	2006	6.2	-	22.4
Nairiku/MYG011EW.AT2	Nairiku/MYG011NS.AT2	Nairiku	MYG011	2008	7.2	-	97.0
Norcia/F-BEV-EW.AT2	Norcia/F-BEV-NS.AT2	Norcia, Italy	Bevagna	1979	5.9	31.4	-
Northridge1/0141-360.AT2	Northridge1/WON095.AT2	Northridge-01	LA - Griffith Park Observatory	1994	6.7	23.8	-
Northridge1/5108-090.AT2	Northridge1/5108-360.AT2	Northridge-01	Santa Susana Ground	1994	6.7	16.7	-
Northridge1/ACI270.AT2	Northridge1/ATB000.AT2	Northridge-01	Anacapa Island	1994	6.7	68.9	-
Northridge1/ATB090.AT2	Northridge1/HOW060.AT2	Northridge-01	Antelope Buttes	1994	6.7	46.9	-
Northridge1/CHL160.AT2	Northridge1/0141-270.AT2	Northridge-01	LA - Chalon Rd	1994	6.7	20.4	-
Northridge1/HOW330.AT2	Northridge1/CHL070.AT2	Northridge-01	Burbank - Howard Rd.	1994	6.7	16.9	-
Northridge1/L04000.AT2	Northridge1/L04090.AT2	Northridge-01	Lake Hughes #4 - Camp Mend	1994	6.7	31.7	-
Northridge1/LA0090.AT2	Northridge1/L04-UP.AT2	Northridge-01	LA 00	1994	6.7	19.1	-
Northridge1/LIT090.AT2	Northridge1/LIT180.AT2	Northridge-01	Littlerock - Brainard Can	1994	6.7	46.6	-
Northridge1/LV1000.AT2	Northridge1/LV1090.AT2	Northridge-01	Leona Valley #1	1994	6.7	37.2	-
Northridge1/LV3000.AT2	Northridge1/LV3090.AT2	Northridge-01	Leona Valley #3	1994	6.7	37.3	-

Northridge1/MTW000.AT2	Northridge1/MTW090.AT2	Northridge-01	Mt Wilson - CIT Seis Sta	1994	6.7	35.9	-
Northridge1/PAC175.AT2	Northridge1/PAC265.AT2	Northridge-01	Pacoima Dam (downstr)	1994	6.7	7.0	-
Northridge1/PUL104.AT2	Northridge1/PUL194.AT2	Northridge-01	Pacoima Dam (upper left)	1994	6.7	7.0	-
Northridge1/SAN090.AT2	Northridge1/SAN180.AT2	Northridge-01	Sandberg - Bald Mtn	1994	6.7	41.6	-
Northridge1/VAS000.AT2	Northridge1/VAS090.AT2	Northridge-01	Vasquez Rocks Park	1994	6.7	23.6	-
Northridge1/WON185.AT2	Northridge1/LA0000.AT2	Northridge-01	LA - Wonderland Ave	1994	6.7	20.3	-
Northridge1/WWJ090.AT2	Northridge1/WWJ180.AT2	Northridge-01	Wrightwood - Jackson Flat	1994	6.7	64.7	-
Noto/GIF006EW.AT2	Noto/GIF006NS.AT2	Noto	GIF006	2007	6.9	-	134.1
NPalmSprings/ARM270.AT2	NPalmSprings/ARM360.AT2	N. Palm Springs	Anza - Red Mountain	1986	6.1	38.4	-
NPalmSprings/ARS270.AT2	NPalmSprings/ARS360.AT2	N. Palm Springs	Santa Rosa Mountain	1986	6.1	39.1	-
NPalmSprings/ATL270.AT2	NPalmSprings/ATL360.AT2	N. Palm Springs	Anza - Tule Canyon	1986	6.1	52.1	-
NPalmSprings/H01000.AT2	NPalmSprings/H01090.AT2	N. Palm Springs	Murrieta Hot Springs	1986	6.1	54.8	-
NPalmSprings/H02000.AT2	NPalmSprings/H02090.AT2	N. Palm Springs	Winchester Bergman Ran	1986	6.1	49.1	-
OshimaIsland/MYG011EW.AT2	OshimaIsland/MYG011NS.AT2	OshimaIsland	MYG011	2003	7.0	-	58.8
PostTohuku/TCG016EW.AT2	PostTohuku/TCG016NS.AT2	PostTohuku	TCG016	2011	7.1	-	63.7
PreTohuku/MYG011EW.AT2	PreTohuku/MYG011NS.AT2	PreTohuku	MYG011	2010	6.7	-	70.3
SanFernando/FTR056.AT2	SanFernando/FTR326.AT2	San Fernando	Fairmont Dam	1971	6.6	30.2	-
SanFernando/L04111.AT2	SanFernando/L04201.AT2	San Fernando	Lake Hughes #4	1971	6.6	25.1	-
SanFernando/PUL164.AT2	SanFernando/PUL254.AT2	San Fernando	Pacoima Dam (upper left abut)	1971	6.6	1.8	-
SanFernando/SAD003.AT2	SanFernando/SAD273.AT2	San Fernando	Santa Anita Dam	1971	6.6	30.7	-
SierraMadre/212V5090.AT2	SierraMadre/212V5180.AT2	Sierra Madre	Vasquez Rocks Park	1991	5.6	39.8	-
Sitka/TTN051-E.AT2	Sitka/TTN051-N.AT2	Sitka, Alaska	Sitka Observatory	1972	7.7	34.6	-
Sukumo/OIT013EW.AT2	Sukumo/OIT013NS.AT2	Sukumo	OIT013	2001	5.6	-	73.8
Tabas/TAB-LN.AT2	Tabas/TAB-TR.AT2	Tabas, Iran	Tabas	1978	7.4	2.0	-
WhittierNarrows1/A-ANG000.AT2	WhittierNarrows1/A-ANG090.AT2	Whitt. Narrows-01	Mill Creek, Angeles Nat For	1987	6.0	36.8	-
WhittierNarrows1/A-CHL030.AT2	WhittierNarrows1/A-CHL120.AT2	Whitt. Narrows-01	LA - Chalon Rd	1987	6.0	35.2	-
WhittierNarrows1/A-VAS000.AT2	WhittierNarrows1/A-VAS090.AT2	Whitt. Narrows-01	Vasquez Rocks Park	1987	6.0	50.4	-
WhittierNarrows1/A-WON075.AT2	WhittierNarrows1/A-WON165.AT2	Whitt. Narrows-01	LA - Wonderland Ave	1987	6.0	27.6	-

Appendix B. Metadata for Long-Duration Motions

File names		Event	Recording Station	Date	Magnitude	$R_{epicenter}$ (km)	$R_{hypocenter}$ (km)
Maule/AngolEW.AT2	Maule/AngolNS.AT2	Maule, Chile	Angol	2010	8.8	212.0	209.0
Maule/ConstitucionEW.AT2	Maule/ConstitucionNS.AT2	Maule, Chile	Constitucion	2010	8.8	78.0	70.0
Maule/CopaipoEW.AT2	Maule/CopaipoNS.AT2	Maule, Chile	Copiapo	2010	8.8	975.0	974.0
Maule/CuricoEW.AT2	Maule/CuricoNS.AT2	Maule, Chile	Curico	2010	8.8	174.0	170.0
Maule/HualaneEW.AT2	Maule/HualaneNS.AT2	Maule, Chile	Hualane	2010	8.8	139.0	134.0
Maule/L_SanPedroEW.AT2	Maule/L_SanPedroNS.AT2	Chile2010	SanPedro	2010	8.8	109.1	114.6
Maule/LlolleoEW.AT2	Maule/LlolleoNS.AT2	Maule, Chile	Llolleo	2010	8.8	277.0	275.0
Maule/MaipuEW.AT2	Maule/MaipuNS.AT2	Maule, Chile	Santiago Maipu	2010	8.8	323.0	321.0
Maule/MatanzasEW.AT2	Maule/MatanzasNS.AT2	Maule, Chile	Matanzas	2010	8.8	233.0	230.0
Maule/PapudoEW.AT2	Maule/PapudoNS.AT2	Maule, Chile	Papudo	2010	8.8	397.0	395.0
Maule/PenalolenEW.AT2	Maule/PenalolenNS.AT2	Maule, Chile	Santiago Penalolen	2010	8.8	334.0	332.0
Maule/PuentaAltoNS.AT2	Maule/PuenteAltoEW.AT2	Maule, Chile	Santiago Puente Alto	2010	8.8	327.0	325.0
Maule/SantiagoCentroEW.AT2	Maule/SantiagoCentroNS.AT2	Maule, Chile	Santiago Centro	2010	8.8	333.0	331.0
Maule/SantiagoLaFloridaEW.AT2	Maule/SantiagoLaFloridaNS.AT2	Maule, Chile	Santiago la Florida	2010	8.8	332.0	330.0
Maule/TalcaEW.AT2	Maule/TalcaNS.AT2	Maule, Chile	Talca	2010	8.8	118.0	113.0
Maule/ValdiviaEW.AT2	Maule/ValdiviaNS.AT2	Maule, Chile	Valdivia	2010	8.8	439.0	438.0
Maule/ValparaisoAlmendralEW.AT2	Maule/ValparaisoAlmendralNS.AT2	Maule, Chile	Valparaiso Almendral	2010	8.8	338.0	336.0
Maule/ValparaisoUTFSMEW.AT2	Maule/ValparaisoUTFSMNS.AT2	Maule, Chile	Valparaiso UTFSM	2010	8.8	339.0	337.0
Maule/VinaDelMarCentroEW.AT2	Maule/VinaDelMarCentroNS.AT2	Maule, Chile	Vina del mar Centro	2010	8.8	340.0	338.0
Maule/VinaDelMarElSaltoEW.AT2	Maule/VinaDelMarElSaltoNS.AT2	Maule, Chile	Vina del mar el Salto	2010	8.8	338.0	336.0
Michoacan/L_CaletaDeCamposEW.AT2	Michoacan/L_CaletaDeCamposNS.AT2	Michoacan	CaletaDeCampos	1985	8.1	27.2	38.3
Michoacan/L_LaUnionEW.AT2	Michoacan/L_LaUnionNS.AT2	Michoacan	LaUnion	1985	8.1	79.4	83.9
Michoacan/L_PapanoaEW.AT2	Michoacan/L_PapanoaNS.AT2	Michoacan	Papanoa	1985	8.1	184.2	186.2
Michoacan/L_SuchilEW.AT2	Michoacan/L_SuchilNS.AT2	Michoacan	Suchil	1985	8.1	226.4	228.0
Michoacan/L_VillitaEW.AT2	Michoacan/L_VillitaNS.AT2	Michoacan	Villita	1985	8.1	39.4	47.8
Michoacan/L_ZijuantanejoEW.AT2	Michoacan/L_ZijuantanejoNS.AT2	Michoacan	Zijuantanejo	1985	8.1	129.8	132.6

Peru1966/L_Arequipa008.AT2	Peru1966/L_Arequipa282.AT2	Peru1966	Island	1966	8.0	237.0	240.0
SumatraFS/L_WestSumatraEW.AT2	SumatraFS/L_WestSumatraNS.AT2	SumatraFS	Sikuai	2007	7.9	164.6	167.3
Tohuku/L_AOM007EW.AT2	Tohuku/L_AOM007NS.AT2	Tohuku	AOM007	2011	9.0	381.2	381.9
Tohuku/L_CHB002EW.AT2	Tohuku/L_CHB002NS.AT2	Tohuku	CHB002	2011	9.0	362.8	363.6
Tohuku/L_CHB004EW.AT2	Tohuku/L_CHB004NS.AT2	Tohuku	CHB004	2011	9.0	316.8	317.7
Tohuku/L_CHB012EW.AT2	Tohuku/L_CHB012NS.AT2	Tohuku	CHB012	2011	9.0	353.7	354.5
Tohuku/L_CHB028EW.AT2	Tohuku/L_CHB028NS.AT2	Tohuku	CHB028	2011	9.0	360.3	361.1
Tohuku/L_FKS001EW.AT2	Tohuku/L_FKS001NS.AT2	Tohuku	FKS001	2011	9.0	175.3	176.9
Tohuku/L_FKS002EW.AT2	Tohuku/L_FKS002NS.AT2	Tohuku	FKS002	2011	9.0	202.4	203.8
Tohuku/L_FKS003EW.AT2	Tohuku/L_FKS003NS.AT2	Tohuku	FKS003	2011	9.0	214.1	215.4
Tohuku/L_FKS004EW.AT2	Tohuku/L_FKS004NS.AT2	Tohuku	FKS004	2011	9.0	193.5	195.0
Tohuku/L_FKS006EW.AT2	Tohuku/L_FKS006NS.AT2	Tohuku	FKS006	2011	9.0	196.2	197.7
Tohuku/L_FKS011EW.AT2	Tohuku/L_FKS011NS.AT2	Tohuku	FKS011	2011	9.0	203.0	204.4
Tohuku/L_FKS012EW.AT2	Tohuku/L_FKS012NS.AT2	Tohuku	FKS012	2011	9.0	222.2	223.5
Tohuku/L_FKS013EW.AT2	Tohuku/L_FKS013NS.AT2	Tohuku	FKS013	2011	9.0	230.1	231.4
Tohuku/L_FKS014EW.AT2	Tohuku/L_FKS014NS.AT2	Tohuku	FKS014	2011	9.0	251.8	253.0
Tohuku/L_FKS015EW.AT2	Tohuku/L_FKS015NS.AT2	Tohuku	FKS015	2011	9.0	247.7	248.9
Tohuku/L_FKS017EW.AT2	Tohuku/L_FKS017NS.AT2	Tohuku	FKS017	2011	9.0	236.7	237.9
Tohuku/L_FKS019EW.AT2	Tohuku/L_FKS019NS.AT2	Tohuku	FKS019	2011	9.0	220.9	222.2
Tohuku/L_FKS020EW.AT2	Tohuku/L_FKS020NS.AT2	Tohuku	FKS020	2011	9.0	250.5	251.7
Tohuku/L_FKS023EW.AT2	Tohuku/L_FKS023NS.AT2	Tohuku	FKS023	2011	9.0	267.6	268.7
Tohuku/L_FKS024EW.AT2	Tohuku/L_FKS024NS.AT2	Tohuku	FKS024	2011	9.0	252.6	253.8
Tohuku/L_FKS031EW.AT2	Tohuku/L_FKS031NS.AT2	Tohuku	FKS031	2011	9.0	198.0	199.5
Tohuku/L_GNM009EW.AT2	Tohuku/L_GNM009NS.AT2	Tohuku	GNM009	2011	9.0	362.6	363.4
Tohuku/L_IBR001EW.AT2	Tohuku/L_IBR001NS.AT2	Tohuku	IBR001	2011	9.0	262.7	263.8
Tohuku/L_IBR002EW.AT2	Tohuku/L_IBR002NS.AT2	Tohuku	IBR002	2011	9.0	241.4	242.6
Tohuku/L_IBR006EW.AT2	Tohuku/L_IBR006NS.AT2	Tohuku	IBR006	2011	9.0	282.7	283.7
Tohuku/L_IBR007EW.AT2	Tohuku/L_IBR007NS.AT2	Tohuku	IBR007	2011	9.0	274.4	275.4
Tohuku/L_IBR008EW.AT2	Tohuku/L_IBR008NS.AT2	Tohuku	IBR008	2011	9.0	319.9	320.8
Tohuku/L_IBR010EW.AT2	Tohuku/L_IBR010NS.AT2	Tohuku	IBR010	2011	9.0	329.4	330.3

Tohuku/L_IBR011EW.AT2	Tohuku/L_IBR011NS.AT2	Tohuku	IBR011	2011	9.0	325.0	325.9
Tohuku/L_IBR012EW.AT2	Tohuku/L_IBR012NS.AT2	Tohuku	IBR012	2011	9.0	307.0	307.9
Tohuku/L_IBR014EW.AT2	Tohuku/L_IBR014NS.AT2	Tohuku	IBR014	2011	9.0	321.9	322.8
Tohuku/L_IBR017EW.AT2	Tohuku/L_IBR017NS.AT2	Tohuku	IBR017	2011	9.0	323.0	323.9
Tohuku/L_IBR018EW.AT2	Tohuku/L_IBR018NS.AT2	Tohuku	IBR018	2011	9.0	302.0	302.9
Tohuku/L_IWT001EW.AT2	Tohuku/L_IWT001NS.AT2	Tohuku	IWT001	2011	9.0	286.7	287.7
Tohuku/L_IWT005EW.AT2	Tohuku/L_IWT005NS.AT2	Tohuku	IWT005	2011	9.0	201.0	202.4
Tohuku/L_IWT009EW.AT2	Tohuku/L_IWT009NS.AT2	Tohuku	IWT009	2011	9.0	172.6	174.3
Tohuku/L_IWT011EW.AT2	Tohuku/L_IWT011NS.AT2	Tohuku	IWT011	2011	9.0	198.3	199.8
Tohuku/L_IWT012EW.AT2	Tohuku/L_IWT012NS.AT2	Tohuku	IWT012	2011	9.0	212.1	213.5
Tohuku/L_IWT013EW.AT2	Tohuku/L_IWT013NS.AT2	Tohuku	IWT013	2011	9.0	190.0	191.5
Tohuku/L_IWT017EW.AT2	Tohuku/L_IWT017NS.AT2	Tohuku	IWT017	2011	9.0	221.5	222.9
Tohuku/L_IWT018EW.AT2	Tohuku/L_IWT018NS.AT2	Tohuku	IWT018	2011	9.0	242.0	243.2
Tohuku/L_IWT019EW.AT2	Tohuku/L_IWT019NS.AT2	Tohuku	IWT019	2011	9.0	226.5	227.8
Tohuku/L_IWT020EW.AT2	Tohuku/L_IWT020NS.AT2	Tohuku	IWT020	2011	9.0	240.5	241.8
Tohuku/L_IWT021EW.AT2	Tohuku/L_IWT021NS.AT2	Tohuku	IWT021	2011	9.0	265.2	266.3
Tohuku/L_IWT026EW.AT2	Tohuku/L_IWT026NS.AT2	Tohuku	IWT026	2011	9.0	209.9	211.2
Tohuku/L_MYG001EW.AT2	Tohuku/L_MYG001NS.AT2	Tohuku	MYG001	2011	9.0	153.3	155.2
Tohuku/L_MYG005EW.AT2	Tohuku/L_MYG005NS.AT2	Tohuku	MYG005	2011	9.0	215.2	216.6
Tohuku/L_MYG006EW.AT2	Tohuku/L_MYG006NS.AT2	Tohuku	MYG006	2011	9.0	180.8	182.4
Tohuku/L_MYG007EW.AT2	Tohuku/L_MYG007NS.AT2	Tohuku	MYG007	2011	9.0	158.1	159.9
Tohuku/L_MYG008EW.AT2	Tohuku/L_MYG008NS.AT2	Tohuku	MYG008	2011	9.0	141.8	143.8
Tohuku/L_MYG009EW.AT2	Tohuku/L_MYG009NS.AT2	Tohuku	MYG009	2011	9.0	182.7	184.3
Tohuku/L_MYG010EW.AT2	Tohuku/L_MYG010NS.AT2	Tohuku	MYG010	2011	9.0	149.3	151.2
Tohuku/L_MYG014EW.AT2	Tohuku/L_MYG014NS.AT2	Tohuku	MYG014	2011	9.0	201.1	202.6
Tohuku/L_MYG015EW.AT2	Tohuku/L_MYG015NS.AT2	Tohuku	MYG015	2011	9.0	178.2	179.8
Tohuku/L_MYG016EW.AT2	Tohuku/L_MYG016NS.AT2	Tohuku	MYG016	2011	9.0	199.7	201.2
Tohuku/L_MYG017EW.AT2	Tohuku/L_MYG017NS.AT2	Tohuku	MYG017	2011	9.0	185.7	187.2
Tohuku/L_SIT004EW.AT2	Tohuku/L_SIT004NS.AT2	Tohuku	SIT004	2011	9.0	396.5	397.3
Tohuku/L_TCG001EW.AT2	Tohuku/L_TCG001NS.AT2	Tohuku	TCG001	2011	9.0	275.1	276.2

Tohuku/L_TCG003EW.AT2	Tohuku/L_TCG003NS.AT2	Tohuku	TCG003	2011	9.0	310.7	311.6
Tohuku/L_TCG004EW.AT2	Tohuku/L_TCG004NS.AT2	Tohuku	TCG004	2011	9.0	334.8	335.8
Tohuku/L_TCG005EW.AT2	Tohuku/L_TCG005NS.AT2	Tohuku	TCG005	2011	9.0	294.3	295.3
Tohuku/L_TCG006EW.AT2	Tohuku/L_TCG006NS.AT2	Tohuku	TCG006	2011	9.0	280.7	281.8
Tohuku/L_TCG008EW.AT2	Tohuku/L_TCG008NS.AT2	Tohuku	TCG008	2011	9.0	320.1	321.0
Tohuku/L_TCG012EW.AT2	Tohuku/L_TCG012NS.AT2	Tohuku	TCG012	2011	9.0	334.1	334.9
Tohuku/L_TCG013EW.AT2	Tohuku/L_TCG013NS.AT2	Tohuku	TCG013	2011	9.0	308.5	309.4
Tohuku/L_TCG016EW.AT2	Tohuku/L_TCG016NS.AT2	Tohuku	TCG016	2011	9.0	292.8	293.8
Tohuku/L_TKY017EW.AT2	Tohuku/L_TKY017NS.AT2	Tohuku	TKY017	2011	9.0	379.6	380.4
Tohuku/L_TKY026EW.AT2	Tohuku/L_TKY026NS.AT2	Tohuku	TKY026	2011	9.0	374.4	375.1
Tohuku/L_YMT006EW.AT2	Tohuku/L_YMT006NS.AT2	Tohuku	YMT006	2011	9.0	227.7	229.0
Valparaiso/L_Cauquenes-EW.AT2	Valparaiso/L_Cauquenes-NS.AT2	Valparaiso	Cauquenes	1985	7.8	320.0	321.7
Valparaiso/L_Constitucion-EW.AT2	Valparaiso/L_Constitucion-NS.AT2	Valparaiso	Cotitucion	1985	7.8	233.3	235.7
Valparaiso/L_Endesa-EW.AT2	Valparaiso/L_Endesa-NS.AT2	Valparaiso	Endesa	1985	7.8	-	-
Valparaiso/L_Hualane-EW.AT2	Valparaiso/L_Hualane-NS.AT2	Valparaiso	Hualane	1985	7.8	204.1	206.8
Valparaiso/L_Illapel-340.AT2	Valparaiso/L_Illapel-70.AT2	Valparaiso	Illapel	1985	7.8	179.9	182.9
Valparaiso/L_Iloca-EW.AT2	Valparaiso/L_Iloca-NS.AT2	Valparaiso	Iloca	1985	7.8	201.1	203.8
Valparaiso/L_Laligua-290.AT2	Valparaiso/L_Laligue-200.AT2	Valparaiso	Laligua	1985	7.8	95.5	101.0
Valparaiso/L_Llayllay-190.AT2	Valparaiso/L_Llayllay-280.AT2	Valparaiso	Llayllay	1985	7.8	89.8	95.6
Valparaiso/L_Llolleo-010.AT2	Valparaiso/L_Llolleo-100.AT2	Valparaiso	Llolleo	1985	7.8	60.0	68.5
Valparaiso/L_LosVilos-EW.AT2	Valparaiso/L_LosVilos-NS.AT2	Valparaiso	LosVilos	1985	7.8	139.5	143.4
Valparaiso/L_Melipilla-EW.AT2	Valparaiso/L_Melipilla-NS.AT2	Valparaiso	Melipilla	1985	7.8	85.6	91.7
Valparaiso/L_Papudo-140.AT2		Valparaiso	Papudo	1985	7.8	79.9	86.4
Valparaiso/L_Pichilemu-EW.AT2	Valparaiso/L_Pichilemu-NS.AT2	Valparaiso	Pichilemu	1985	7.8	139.1	143.0
Valparaiso/L_Quintay-EW.AT2	Valparaiso/L_Quintay-NS.AT2	Valparaiso	Quintay	1985	7.8	53.4	62.8
Valparaiso/L_Rapel-EW.AT2	Valparaiso/L_Rapel-NS.AT2	Valparaiso	Rapel	1985	7.8	103.0	108.2
Valparaiso/L_SanFelipe-080.AT2	Valparaiso/L_SanFelipe-170.AT2	Valparaiso	SanFelipe	1985	7.8	114.8	119.4
Valparaiso/L_SanFern-EW.AT2	Valparaiso/L_SanFern-NS.AT2	Valparaiso	SanFern	1985	7.8	181.7	184.7
Valparaiso/L_SanIsidroEW.AT2	Valparaiso/L_SanIsidro-NS.AT2	Valparaiso	SanIsidro	1985	7.8	-	-
Valparaiso/L_Talca-010.AT2	Valparaiso/L_Talca-280.AT2	Valparaiso	Talca	1985	7.8	222.3	224.7

Valparaiso/L_ValElAlm-050.AT2	Valparaiso/L_ValElAlm-140.AT2	Valparaiso	ValElAlm	1985	7.8	25.8	41.9
Valparaiso/L_ValpoUFSM-160.AT2	Valparaiso/L_ValpoUFSM-070.AT2	Valparaiso	ValopUFSM	1985	7.8	124.9	129.2
Valparaiso/L_Ventanas-EW.AT2	Valparaiso/L_Ventanas-NS.AT2	Valparaiso	Ventanas	1985	7.8	26.1	42.1
Valparaiso/L_Vina-200.AT2	Valparaiso/L_Vina-290.AT2	Valparaiso	Vina	1985	7.8	30.8	45.2
Valparaiso/L_Zapallar-EW.AT2	Valparaiso/L_Zapallar-NS.AT2	Valparaiso	Zapallar	1985	7.8	73.2	80.3

Appendix C. Metadata for Near-Fault Motions

File names		Event	Recording Station	Date	M_w	R_{rup} (km)	R_{ep} (km)
FaultNormal/P1_original.AT2	FaultParallel/P1_original_FP.AT2	San Fernando	Pacoima Dam (upper left abut)	1971	6.6	1.8	11.9
FaultNormal/P2_original.AT2	FaultParallel/P2_original_FP.AT2	Coyote Lake	Gilroy Array #6	1979	5.7	3.1	4.4
FaultNormal/P3_original.AT2	FaultParallel/P3_original_FP.AT2	Imperial Valley-06	Aeropuerto Mexicali	1979	6.5	0.3	2.5
FaultNormal/P4_original.AT2	FaultParallel/P4_original_FP.AT2	Imperial Valley-06	Agrarias	1979	6.5	0.7	2.6
FaultNormal/P5_original.AT2	FaultParallel/P5_original_FP.AT2	Imperial Valley-06	Brawley Airport	1979	6.5	10.4	43.2
FaultNormal/P6_original.AT2	FaultParallel/P6_original_FP.AT2	Imperial Valley-06	EC County Center FF	1979	6.5	7.3	29.1
FaultNormal/P7_original.AT2	FaultParallel/P7_original_FP.AT2	Imperial Valley-06	EC Meloland Overpass FF	1979	6.5	0.1	19.4
FaultNormal/P8_original.AT2	FaultParallel/P8_original_FP.AT2	Imperial Valley-06	El Centro Array #10	1979	6.5	6.2	26.3
FaultNormal/P9_original.AT2	FaultParallel/P9_original_FP.AT2	Imperial Valley-06	El Centro Array #11	1979	6.5	12.5	29.4
FaultNormal/P10_original.AT2	FaultParallel/P10_original_FP.AT1	Imperial Valley-06	El Centro Array #3	1979	6.5	12.9	28.7
FaultNormal/P11_original.AT2	FaultParallel/P11_original_FP.AT2	Imperial Valley-06	El Centro Array #4	1979	6.5	7.1	27.1
FaultNormal/P12_original.AT2	FaultParallel/P12_original_FP.AT2	Imperial Valley-06	El Centro Array #5	1979	6.5	4.0	27.8
FaultNormal/P13_original.AT2	FaultParallel/P13_original_FP.AT2	Imperial Valley-06	El Centro Array #6	1979	6.5	1.4	27.5
FaultNormal/P14_original.AT2	FaultParallel/P14_original_FP.AT2	Imperial Valley-06	El Centro Array #7	1979	6.5	0.6	27.6
FaultNormal/P15_original.AT2	FaultParallel/P15_original_FP.AT2	Imperial Valley-06	El Centro Array #8	1979	6.5	3.9	28.1
FaultNormal/P16_original.AT2	FaultParallel/P16_original_FP.AT2	Imperial Valley-06	El Centro Differential Array	1979	6.5	5.1	27.2
FaultNormal/P17_original.AT2	FaultParallel/P17_original_FP.AT2	Imperial Valley-06	Holtville Post Office	1979	6.5	7.7	19.8
FaultNormal/P18_original.AT2	FaultParallel/P18_original_FP.AT2	Mammoth Lakes-06	Long Valley Dam (Upr L Abut)	1980	5.9	-	14.0
FaultNormal/P19_original.AT2	FaultParallel/P19_original_FP.AT2	Irpinia, Italy-01	Sturno	1980	6.9	10.8	30.4
FaultNormal/P20_original.AT2	FaultParallel/P20_original_FP.AT2	Westmorland	Parachute Test Site	1981	5.9	16.7	20.5
FaultNormal/P21_original.AT2	FaultParallel/P21_original_FP.AT2	Coalinga-05	Oil City	1983	5.8	-	4.6
FaultNormal/P22_original.AT2	FaultParallel/P22_original_FP.AT2	Coalinga-05	Transmitter Hill	1983	5.8	-	6.0
FaultNormal/P23_original.AT2	FaultParallel/P23_original_FP.AT2	Coalinga-07	Coalinga-14th & Elm (Old CHP)	1983	5.2	-	9.6

FaultNormal/P24_original.AT2	FaultParallel/P24_original_FP.AT2	Morgan Hill	Coyote Lake Dam (SW Abut)	1984	6.2	0.5	24.6
FaultNormal/P25_original.AT2	FaultParallel/P25_original_FP.AT2	Morgan Hill	Gilroy Array #6	1984	6.2	9.9	36.3
FaultNormal/P26_original.AT2	FaultParallel/P26_original_FP.AT2	Taiwan SMART1(40)	SMART1 C00	1986	6.3	-	68.2
FaultNormal/P27_original.AT2	FaultParallel/P27_original_FP.AT2	Taiwan SMART1(40)	SMART1 M07	1986	6.3	-	67.2
FaultNormal/P28_original.AT2	FaultParallel/P28_original_FP.AT2	N. Palm Springs	North Palm Springs	1986	6.1	4.0	10.6
FaultNormal/P29_original.AT2	FaultParallel/P29_original_FP.AT2	San Salvador	Geotech Investig Center	1986	5.8	6.3	7.9
FaultNormal/P30_original.AT2	FaultParallel/P30_original_FP.AT2	Whittier Narrows-01	Downey - Co Maint Bldg	1987	6.0	20.8	16.0
FaultNormal/P31_original.AT2	FaultParallel/P31_original_FP.AT2	Whittier Narrows-01	LB - Orange Ave	1987	6.0	24.5	20.7
FaultNormal/P32_original.AT2	FaultParallel/P32_original_FP.AT2	Superstition Hills-02	Parachute Test Site	1987	6.5	1.0	16.0
FaultNormal/P33_original.AT2	FaultParallel/P33_original_FP.AT2	Loma Prieta	Alameda Naval Air Stn Hanger	1989	6.9	71.0	90.8
FaultNormal/P34_original.AT2	FaultParallel/P34_original_FP.AT2	Loma Prieta	Gilroy Array #2	1989	6.9	11.1	29.8
FaultNormal/P35_original.AT2	FaultParallel/P35_original_FP.AT2	Loma Prieta	Oakland - Outer Harbor Wharf	1989	6.9	74.3	94.0
FaultNormal/P36_original.AT2	FaultParallel/P36_original_FP.AT2	Loma Prieta	Saratoga - Aloha Ave	1989	6.9	8.5	27.2
FaultNormal/P37_original.AT2	FaultParallel/P37_original_FP.AT2	Erzican, Turkey	Erzincan	1992	6.7	4.4	9.0
FaultNormal/P38_original.AT2	FaultParallel/P38_original_FP.AT2	Cape Mendocino	Petrolia	1992	7.0	8.2	4.5
FaultNormal/P39_original.AT2	FaultParallel/P39_original_FP.AT2	Landers	Barstow	1992	7.3	34.9	94.8
FaultNormal/P40_original.AT2	FaultParallel/P40_original_FP.AT2	Landers	Lucerne	1992	7.3	2.2	44.0
FaultNormal/P41_original.AT2	FaultParallel/P41_original_FP.AT2	Landers	Yermo Fire Station	1992	7.3	23.6	86.0
FaultNormal/P42_original.AT2	FaultParallel/P42_original_FP.AT2	Northridge-01	Jensen Filter Plant	1994	6.7	5.4	13.0
FaultNormal/P43_original.AT2	FaultParallel/P43_original_FP.AT2	Northridge-01	Jensen Filter Plant Generator	1994	6.7	5.4	13.0
FaultNormal/P44_original.AT2	FaultParallel/P44_original_FP.AT2	Northridge-01	LA - Wadsworth VA Hospital North	1994	6.7	23.6	19.6
FaultNormal/P45_original.AT2	FaultParallel/P45_original_FP.AT2	Northridge-01	LA Dam	1994	6.7	5.9	11.8
FaultNormal/P46_original.AT2	FaultParallel/P46_original_FP.AT2	Northridge-01	Newhall - W Pico Canyon Rd.	1994	6.7	5.5	21.6
FaultNormal/P47_original.AT2	FaultParallel/P47_original_FP.AT2	Northridge-01	Pacoima Dam (downstr)	1994	6.7	7.0	20.4
FaultNormal/P48_original.AT2	FaultParallel/P48_original_FP.AT2	Northridge-01	Pacoima Dam (upper left)	1994	6.7	7.0	20.4
FaultNormal/P49_original.AT2	FaultParallel/P49_original_FP.AT2	Northridge-01	Rinaldi Receiving Sta	1994	6.7	6.5	10.9
FaultNormal/P50_original.AT2	FaultParallel/P50_original_FP.AT2	Northridge-01	Sylmar - Converter Sta	1994	6.7	5.4	13.1
FaultNormal/P51_original.AT2	FaultParallel/P51_original_FP.AT2	Northridge-01	Sylmar - Converter Sta East	1994	6.7	5.2	13.6
FaultNormal/P52_original.AT2	FaultParallel/P52_original_FP.AT2	Northridge-01	Sylmar - Olive View Med FF	1994	6.7	5.3	16.8
FaultNormal/P53_original.AT2	FaultParallel/P53_original_FP.AT2	Kobe, Japan	Takarazuka	1995	6.9	0.3	38.6

FaultNormal/P54_original.AT2	FaultParallel/P54_original_FP.AT2	Kobe, Japan	Takatori	1995	6.9	1.5	13.1
FaultNormal/P55_original.AT2	FaultParallel/P55_original_FP.AT2	Kocaeli, Turkey	Gebze	1999	7.5	10.9	47.0
FaultNormal/P56_original.AT2	FaultParallel/P56_original_FP.AT2	Chi-Chi, Taiwan	CHY006	1999	7.6	9.8	40.5
FaultNormal/P57_original.AT2	FaultParallel/P57_original_FP.AT2	Chi-Chi, Taiwan	CHY035	1999	7.6	12.7	43.9
FaultNormal/P58_original.AT2	FaultParallel/P58_original_FP.AT2	Chi-Chi, Taiwan	CHY101	1999	7.6	10.0	32.0
FaultNormal/P59_original.AT2	FaultParallel/P59_original_FP.AT2	Chi-Chi, Taiwan	TAP003	1999	7.6	102.4	151.7
FaultNormal/P60_original.AT2	FaultParallel/P60_original_FP.AT2	Chi-Chi, Taiwan	TCU029	1999	7.6	28.1	79.2
FaultNormal/P61_original.AT2	FaultParallel/P61_original_FP.AT2	Chi-Chi, Taiwan	TCU031	1999	7.6	30.2	80.1
FaultNormal/P62_original.AT2	FaultParallel/P62_original_FP.AT2	Chi-Chi, Taiwan	TCU034	1999	7.6	35.7	87.9
FaultNormal/P63_original.AT2	FaultParallel/P63_original_FP.AT2	Chi-Chi, Taiwan	TCU036	1999	7.6	19.8	67.8
FaultNormal/P64_original.AT2	FaultParallel/P64_original_FP.AT2	Chi-Chi, Taiwan	TCU038	1999	7.6	25.4	73.1
FaultNormal/P65_original.AT2	FaultParallel/P65_original_FP.AT2	Chi-Chi, Taiwan	TCU040	1999	7.6	22.1	69.0
FaultNormal/P66_original.AT2	FaultParallel/P66_original_FP.AT2	Chi-Chi, Taiwan	TCU042	1999	7.6	26.3	78.4
FaultNormal/P67_original.AT2	FaultParallel/P67_original_FP.AT2	Chi-Chi, Taiwan	TCU046	1999	7.6	16.7	68.9
FaultNormal/P68_original.AT2	FaultParallel/P68_original_FP.AT2	Chi-Chi, Taiwan	TCU049	1999	7.6	3.8	38.9
FaultNormal/P69_original.AT2	FaultParallel/P69_original_FP.AT2	Chi-Chi, Taiwan	TCU053	1999	7.6	6.0	41.2
FaultNormal/P70_original.AT2	FaultParallel/P70_original_FP.AT2	Chi-Chi, Taiwan	TCU054	1999	7.6	5.3	37.6
FaultNormal/P71_original.AT2	FaultParallel/P71_original_FP.AT2	Chi-Chi, Taiwan	TCU056	1999	7.6	10.5	39.7
FaultNormal/P72_original.AT2	FaultParallel/P72_original_FP.AT2	Chi-Chi, Taiwan	TCU060	1999	7.6	8.5	45.4
FaultNormal/P73_original.AT2	FaultParallel/P73_original_FP.AT2	Chi-Chi, Taiwan	TCU065	1999	7.6	0.6	26.7
FaultNormal/P74_original.AT2	FaultParallel/P74_original_FP.AT2	Chi-Chi, Taiwan	TCU068	1999	7.6	0.3	47.9
FaultNormal/P75_original.AT2	FaultParallel/P75_original_FP.AT2	Chi-Chi, Taiwan	TCU075	1999	7.6	0.9	20.7
FaultNormal/P76_original.AT2	FaultParallel/P76_original_FP.AT2	Chi-Chi, Taiwan	TCU076	1999	7.6	2.8	16.0
FaultNormal/P77_original.AT2	FaultParallel/P77_original_FP.AT2	Chi-Chi, Taiwan	TCU082	1999	7.6	5.2	36.2
FaultNormal/P78_original.AT2	FaultParallel/P78_original_FP.AT2	Chi-Chi, Taiwan	TCU087	1999	7.6	7.0	55.6
FaultNormal/P79_original.AT2	FaultParallel/P79_original_FP.AT2	Chi-Chi, Taiwan	TCU098	1999	7.6	47.7	99.7
FaultNormal/P80_original.AT2	FaultParallel/P80_original_FP.AT2	Chi-Chi, Taiwan	TCU101	1999	7.6	2.1	45.1
FaultNormal/P81_original.AT2	FaultParallel/P81_original_FP.AT2	Chi-Chi, Taiwan	TCU102	1999	7.6	1.5	45.6
FaultNormal/P82_original.AT2	FaultParallel/P82_original_FP.AT2	Chi-Chi, Taiwan	TCU103	1999	7.6	6.1	52.4
FaultNormal/P83_original.AT2	FaultParallel/P83_original_FP.AT2	Chi-Chi, Taiwan	TCU104	1999	7.6	12.9	49.3

FaultNormal/P84_original.AT2	FaultParallel/P84_original_FP.AT2	Chi-Chi, Taiwan	TCU128	1999	7.6	13.2	63.3
FaultNormal/P85_original.AT2	FaultParallel/P85_original_FP.AT2	Chi-Chi, Taiwan	TCU136	1999	7.6	8.3	48.8
FaultNormal/P86_original.AT2	FaultParallel/P86_original_FP.AT2	Northwest China-03	Jiashi	1997	6.1	-	19.1
FaultNormal/P87_original.AT2	FaultParallel/P87_original_FP.AT2	Yountville	Napa Fire Station #3	2000	5.0	-	9.9
FaultNormal/P88_original.AT2	FaultParallel/P88_original_FP.AT2	Chi-Chi, Taiwan-03	CHY024	1999	6.2	19.7	25.5
FaultNormal/P89_original.AT2	FaultParallel/P89_original_FP.AT2	Chi-Chi, Taiwan-03	CHY080	1999	6.2	22.4	29.5
FaultNormal/P90_original.AT2	FaultParallel/P90_original_FP.AT2	Chi-Chi, Taiwan-03	TCU076	1999	6.2	14.7	20.8
FaultNormal/P91_original.AT2	FaultParallel/P91_original_FP.AT2	Chi-Chi, Taiwan-06	CHY101	1999	6.3	36.0	50.0