DESIGN GROUND MOTION LIBRARY

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DESIGN GROUND MOTION LIBRARY

1.0 INTRODUCTION

1.1 OBJECTIVE, SPONSORSHIP, AND LIMITS

This report documents the development of a Design Ground Motion Library (DGML). The objective of the DGML project is to create an electronic library of recorded ground motion acceleration time histories suitable for use by engineering practitioners for time-history dynamic analyses of various facility types in California and other parts of the western United States. The DGML project is jointly sponsored by the California Geological Survey - Strong Motion Instrumentation Program (CGS-SMIP) and the Pacific Earthquake Engineering Research Center - Lifelines Program (PEER-LL). The DGML is currently limited to recorded time histories from shallow crustal earthquakes of the type that occurs in the western United States. Time histories from subduction zone earthquakes are not part of the Library during this project. However, future developments of the DGML could add records from subduction zone earthquakes (appropriate for these types of earthquakes occurring in coastal regions of northwest California, Oregon, Washington, and Alaska) and could also supplement the library of recorded time histories with time histories simulated by ground motion modeling methods.

1.2 EVOLUTION OF DGML CONCEPT

The original concept of the DGML was a “static” library of time history records selected as suitable for certain predefined seismic environment “bins”, characterized by earthquake magnitude ranges, types of faulting, distance ranges, and classes of site conditions, and several period-range “sub-bins” selected as representative for different classes of structures. Fixed sets of records would be selected for each bin and sub-bin. The primary criterion for selecting records was to be the closeness of spectral shapes to shapes defined by current ground motion attenuation relationships over the sub-bin period ranges. However, during the time period of DGML development, it became apparent from research on the relationship of ground motion characteristics and structure response that selecting records to give realistic (not overly conservative) estimates of structural inelastic response for different types of structures required consideration of selection of time histories dependent on ground motion intensity and a wide range of structure characteristics. Work by the PEER Ground Motion Selection and Modification Working Group (GMSM), as presented in the 2006 and 2007 Technical Sessions of the Annual Meetings of the Consortium of Organizations for Strong Motion Observation Systems (COSMOS 2006 and 2007) demonstrated the importance to inelastic response of “conditioning” ground motion response spectra dependent on the intensity of shaking and the characteristics of the structure. These considerations, as well as considerations of a range of preferences by designers and analysts (such as the size of the time history sets) indicated that a “dynamic” library was needed, i.e. a library permitting the tailoring of the selection of time history records to specific project needs and designer preferences. Accordingly a library has been developed that enables the rapid sorting and selection of the time histories from a large ground motion database based on appropriate criteria and user needs rather than having pre-selected fixed record sets.

1.3 PRODUCTS

Products of this project include:

(1) An electronic DGML (Version 2.0) that includes a database of ground motion records, including acceleration time histories and corresponding acceleration response spectra, and a software tool for selecting, scaling, and evaluating time histories for applications. Currently, the electronic DGML is on a DVD-ROM. It could be converted to internet web-based usage.

(2) This report documenting the DGML development (also on the DVD-ROM).

(3) The Users Manual for the DGML, which is included as Appendix A of the report (also on the DVD-ROM).

1.4 PROJECT TEAM

The DGML has been developed by a project team that includes experts in the selection of time history record sets and use of time histories in dynamic analysis of structures. Accordingly, a multi-disciplinary project team of practitioners and researchers in structural engineering, geotechnical engineering, and seismology was formed. The team includes experts in the time history dynamic analysis of buildings, bridges, dams, other heavy civil structures, lifeline structures and systems, and base isolated structures. The project team includes the following organizations and individuals: Geomatrix Consultants, Inc., prime contractor (Robert Youngs, Gang Wang, Maurice Power, Zhihua (Lillian) Li, Faiz Makdisi, and Chih-Cheng Chin); Simpson Gumpertz & Heger, Inc. (Ronald Hamburger and Ronald Mayes); Parsons Brinckerhoff (Roupen Donikian); Quest Structures (Yusof Ghanaat); Pacific Engineering & Analysis (Walter Silva); URS Corporation (Paul Somerville); Earth Mechanics (Ignatius Po Lam); Professors Allin Cornell and Jack Baker, Stanford University; and Professor Stephen Mahin, University of California, Berkeley.

2.0 DGML CAPABILITIES, FEATURES, AND OPERATION

2.1 OVERVIEW

The DGML has the broad capability of searching for time history record sets in the library database on the basis of (1) the characteristics of the recordings in terms of earthquake magnitude and type of faulting, distance, and site characteristics, (2) the response spectral shape of the records in comparison to design or target response spectra, and (3) other record characteristics including duration and the presence of velocity pulses in near-fault time histories. Other criteria and limits can be specified by the user to constrain searches for time histories. Also, supplemental searches can be conducted for individual records or records from selected earthquakes or stations and these records can be evaluated and incorporated in data sets of search results.

Response spectral shape over a period range of significance to structural response has been found to be closely correlated to inelastic structural response and behavior in a number of studies (e.g. Shome et al. 1998; Cordova et al. 2001; Luco and Cornell 2006; Bazurro and Jalayer 2003; Baker and Cornell 2004; Luco and Bazurro 2004; Baker and Cornell 2005, 2006, 2008; GMSM Working Group, 2009). The period range of significance may include periods shorter than the fundamental structure period because of higher-mode effects and periods longer than the fundamental structure period because of structure softening during inelastic response. Although sets of time histories are often formed in practice to provide an aggregate match to a probabilistic response spectrum (equal or uniform hazard spectrum, UHS) for design purposes, there may be conservatisms involved in doing so. As summarized by Cornell (2006), the UHS is not the response spectrum of ground motion from a single earthquake and therefore has an artificial shape. The spectral ordinates at different periods may be driven by two or more different earthquakes and therefore the UHS may be overly broad and thus conservative for a single earthquake. Hazard deaggregation can be carried out to identify the dominant earthquake sources and narrower deterministic scenario earthquake design spectra scaled to the level of the UHS can be defined as appropriate.

It has also been shown that a deterministic scenario earthquake spectrum may also be overly broad if all spectrum ordinates are at a high "epsilon (ε)" value, where (ε) is defined as the number of standard deviations above or below the median spectrum ordinate for a given earthquake, distance, and site condition. In this case, it is technically justifiable and appropriate to define "conditional mean spectra" that are more narrow-banded (Baker and Cornell 2006; Baker 2006; Cornell, 2006). The term "conditional mean spectrum" refers to the mean of spectra that are conditioned on a spectral value at a given period being at ε number of standard deviations above or below the median ground motion for the particular earthquake, distance, and site condition. The conditional mean spectrum is at ε number of standard deviations at the period of conditioning, while the absolute value of the number of standard deviations at other points on the conditional mean spectrum would be less. Figure 1(a) illustrates the construction of a conditional mean spectrum given a target value of spectral acceleration at a particular period on a spectrum constructed for a particular epsilon (in Figure 1(a), $\varepsilon = 2$ at a period of 1 second). It can be seen that at periods away from 1 second, the conditional mean spectrum is below the ε=2 level. The conditional mean spectrum reflects the lack of perfect correlation between spectral accelerations at different periods, so that if a rare high spectral acceleration (e.g. ε=2 value in Figure 1(a)) is observed at one period, it is unlikely that it will be observed at other periods. The steps involved in calculating a conditional mean spectrum are summarized in Figure 1(b). The work of the PEER Ground Motion Selection and Modification Working Group, as presented at the COSMOS 2006 and 2007 Annual Meeting Technical Sessions (COSMOS 2006, 2007) and, at the GEESD IV 2008 Conference (Goulet et al., 2008 and reported on by the GMSM Working Group (2009), illustrated that selecting time histories having response spectral shapes corresponding to the conditional mean spectrum was an effective approach for obtaining a set of time histories giving realistic inelastic structure response. As described in Section 2.3, the DGML software tool enables the user to specify different options, including the conditional mean spectrum option, for constructing a design or target response spectrum and to search for time histories having spectral shapes that are most similar to the target spectrum over a user-defined period range of significance.

A number of studies have shown that strong velocity pulses in ground motion time history records, such as often occur in near-source ground motions due to near-source fault rupture directivity effects, can impose severe demands on structures (e.g. Bertero et al.; 1978; Anderson and Bertero 1987; Hall et al. 1995; Iwan 1997; Krawinkler and Alavi 1998; Alavi and Krawinkler 2001; Menun and Fu 2002; Makris and Black 2003; Mavroeidis et al. 2004; Akkar et al. 2005; Luco and Cornell 2006; Baker and Cornell, 2008). The strongest pulses tend to occur closer to the fault-strike-normal (FN) direction than the fault-strike-parallel (FP) direction (Somerville et al. 1997). FN records having velocity pulses that may be associated with directivity effects have been systematically identified in the PEER NGA database by Baker (2007). (The PEER-NGA database is described in Section 2.2 below.) Records with pulses have been identified by other researchers (e.g. Somerville 2003; Mavroeides and Papageorgiou 2003; Bray and Rodriguez-Marek 2004; Fu and Menun 2004). Records with velocity pulses are discussed in Section 2.4.1 and the presence of velocity pulses in records can be a criterion in searches for records in the DGML.

2.2 DATABASE

The source of the database for the DGML is the PEER Next-Generation Attenuation (NGA) project database of ground motion recordings and supporting information (http://peer.berkeley.edu/nga/). This database was developed as the principal resource for the development of updated attenuation relationships in the NGA research project coordinated by PEER-Lifelines Program (PEER-LL), in partnership with the U.S. Geological Survey (USGS) and the Southern California Earthquake Center (SCEC) (Chiou et al. 2006, 2008; Power et al., 2008). The database represents a comprehensive update and expansion of the pre-existing PEER database (Chiou et al., 2008). The ground motion records are originally from strong motion networks and databases of CGS-CSMIP and USGS and other reliable sources, including selected record sets from international sources. The PEER NGA database includes 3551 three-component recordings from 173 earthquakes and 1456 recording stations. 369 records from the PEER NGA database were not included in the current DGML database of 3182 records. The records were not included for various reasons including one or more of the following: (a) records considered to be from tectonic environments other than shallow crustal earthquakes in active tectonic regions, e.g. records from subduction zones; (b) earthquakes poorly defined; (c) records obtained in recording stations not considered to be sufficiently close to free-field ground surface conditions, e.g. records obtained in basements or on the ground floors of tall buildings; (d) absence of information on soil/geologic conditions at recording stations; (e) records had only one horizontal component; (f) records had not been rotated to FN and FP directions because of absence of information on sensor orientations or fault strike; (g) records of questionable quality; (h) proprietary data; (i) duplicate records; and (j) other reasons. Records selected for the DGML are tabulated in Table B-1 of Appendix B, and records not included and reasons for exclusion are tabulated in Table B-2 (tables available in the electronic version of the report on the DVD). Figure 2 shows the magnitude and distance distribution of the included records.

Acceleration time histories in the DGML that can be searched for on the basis of record characteristics and other criteria (see Section 2.3.2) are horizontal components that have been rotated to FN and FP directions. The use of rotated time histories in the DGML does not imply that they are for use in time history analyses in FN and FP directions only, and they can be used in time history sets in the same manner as time histories in the as-recorded orientations in other databases. The rotation to FN and FP directions does, however, provide additional information with respect to the seismological conditions under which the recordings were obtained, and, as mentioned in Section 2.1, records in the FN direction have been found to often contain strong velocity pulses that may be associated with rupture directivity effects.

Ground motion parameters quantified for time histories in the DGML database are response spectra, peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), significant duration, assessments of the lowest usable frequency (longest usable period) for response spectra, and presence and periods of strong velocity pulses. Significant duration was calculated as the time required to build up from 5% to 95% of the Arias Intensity (a measure of energy) of the acceleration time histories (refer, for example, to Kempton and Stewart (2006) for definitions of Arias Intensity and significant duration). The recommended lowest usable frequency is related to filtering of a record by the record processing organization to remove low-frequency (long-period) noise. Filtering results in suppression of ground motion amplitudes and energy at frequencies lower than the lowest usable frequency such that the motion is not representative of the real ground motion at those frequencies. It is a user's choice in DGML on whether to select or reject a record on the basis of the lowest usable frequency. Because of the suppression of ground motion at frequencies lower than the lowest usable frequency, it is recommended that selected records have lowest usable frequencies equal to or lower than the lowest frequency of interest.

A major effort was made in the PEER-NGA project to systematically evaluate and quantify supporting information (metadata) about the ground motion records, including information about the earthquake, travel path from the earthquake source to the recording station site, and local site conditions. Metadata in the PEER-NGA database are described in the NGA flatfile and documentation: http://peer.berkeley.edu/products/nga_flatfiles_dev.html. Every record in the database was assigned a unique record number (NGA#) for identification purposes.

Metadata that have been included for records in the DGML database are: earthquake name, year, magnitude, and type of faulting; measures of closest distance from earthquake source to recording station site (closest distance to fault rupture surface and Joyner-Boore distance); recording station name; site average shear wave velocity in the upper 30 meters, V_{S30}; and NGA#.

The DGML also provides access to the vertical ground motion time histories and their response spectra if available. Vertical time histories and response spectra are scaled by the same scale factors developed for their horizontal components, and they can be visualized together with the horizontal components. These features are provided as a convenience to users for developing three-component sets of time histories.

2.3 FORMING TIME HISTORY SETS BASED ON RESPONSE SPECTRAL SHAPE AND OTHER CRITERIA FOR HORIZONTAL COMPONENTS

The formation of data sets based on response spectral shape and other criteria is a three-step process: (1) specification of the design or target response spectrum; (2) specification of criteria and limits for conducting searches for time history records; and (3) search of database and selection and evaluation of records.

2.3.1 Step 1 – Developing the Target Spectrum

Three options are provided within the DGML for developing the target spectrum:

Option 1 – Specify Code Spectrum. For this option, the target spectrum is the design earthquake spectrum or the maximum considered earthquake (MCE) spectrum as formulated in the NEHRP Provisions, (BSSC 2003), ASCE Standard ASCE/SEI 7-05 (ASCE 2006), and the International Building Code, (ICC 2006). As indicated in Figure 3, the Code design spectrum is completely specified by three parameters which are obtained using the design ground motion maps and other provisions in the Code document: site-class-adjusted 0.2 second spectral acceleration, S_{DS}; site-class-adjusted 1.0-second spectral acceleration, S_{D1}; and the transition period, T_L, from constant spectral velocity (for which spectral accelerations are proportional to 1/T) to constant spectral displacement (for which spectral accelerations are proportional to $1/T^2$). The user enters the values for these three parameters and the DGML software tool constructs and plots the response spectrum.

Option 2 – User-Defined Spectrum. The user may enter any response spectrum as a table of periods and response spectral accelerations and the tool constructs and plots the spectrum. Such response spectra may be either probabilistic (uniform hazard, UHS) or deterministic (scenario earthquake) response spectra developed by the user.

Option 3 – Spectrum based on PEER Next Generation Attenuation (NGA) Relationships. Developing a spectrum for Option 3 is a special case of Option 2. For Option 3, the tool constructs a deterministic scenario earthquake spectrum using a user-selected set of ground motion attenuation models developed in the NGA project for shallow crustal earthquakes in active tectonic regions. Five different attenuation models were developed in the NGA project: (Abrahamson and Silva 2008; Boore and Atkinson 2008; Campbell and Bozorgnia 2008; Chiou and Youngs 2008a; and Idriss 2008). The applicability of the Idriss (2008) relation is currently restricted to V_{s30} equal to or greater than 450 m/sec. The user enters the earthquake parameters, travel path parameters, and site parameters (e.g., earthquake moment magnitude, type of faulting, fault-to-site distance, site shear wave velocity in the upper 30 meters (V_{S30}), and other parameters needed for the selected NGA models, and the tool constructs the individual response spectra and an average of the spectra for the models. The user also specifies whether the spectrum is a median spectrum or a spectrum at a selected epsilon (ε) number of standard deviations. Figure 4 illustrates individual and averaged NGA response spectra for a scenario earthquake constructed by the software tool. The user also has the option of constructing the response spectrum as a conditional mean spectrum, such as illustrated in Figure 1, using the correlation model of Baker and Jayaram (2008). The equations and steps involved in calculating a conditional mean spectrum are also shown in Figure 1. The construction of the conditional mean spectrum is done by the software tool conditional upon spectral acceleration at level ε for a user-specified $T_{\_eps}$, i.e., $T_{\_eps}$ is the period for which the spectrum is at the number of standard deviations, ε, specified for the attenuation relationships. (Note that the symbol T_1 in Figure 1 is equivalent to the symbol $T_{\_eps}$ as used herein and in the Users Manual, Appendix A.) Multiple conditional mean spectra can be constructed for different periods $T_{\_eps}$. Figure 5 illustrates conceptually construction of a conditional mean spectrum by the software tool. Figure 6 illustrates conceptually construction of conditional mean response spectra for different periods for two scenario earthquakes in order to more closely match, in aggregate, a UHS design spectrum. As shown in Figure 6 for scenario earthquakes A and B, a single conditional mean spectrum for each earthquake could fall substantially below the UHS at periods distant from the period at which the conditional mean spectrum is at the target epsilon. Therefore, as shown in the figure, two (or more) conditional mean spectra could be required for each scenario earthquake to satisfy Code requirements for an aggregate match to the design UHS.

In order to construct a conditional mean spectrum using the DGML tool the user must specify the value of ε. There are a variety of approaches that may be used to select the appropriate value of ε. Many modern PSHA software applications provide information on the values of ε that are representative of the computed ground motion hazard (ε deaggregation). The user can use this information to select an appropriate value of ε. Alternatively, the user may use a target value of spectral acceleration at the spectral period of interest, $T_{\_eps}$, to define the appropriate value of ε. The current version of the DGML tool applies the same value of ε to all of the selected NGA ground motion relationships. The user can adjust the entered value of ε until the computed average conditional mean spectrum matches the target spectral acceleration at $T_{\_eps}$. A third alternative is for the user to construct the conditional mean spectrum outside of the DGML tool and then enter this spectrum using Option 2 – User-Defined Spectrum described above.

2.3.2 Step 2 – Specifying Criteria and Limits for Searches for Time History Records on the Basis of Spectral Shape

A basic criterion used by the DGML to select a representative acceleration time history is that the spectrum of the time history provide a "good match" to the user's target spectrum over the spectral period range of interest. The user defines the period range of interest. The quantitative measure used to evaluate how well a time history conforms to the target spectrum is the mean squared error (MSE) of the difference between the spectral accelerations of the record and the target spectrum, computed using the logarithms of spectral period and spectral acceleration. The DGML tool searches the database for records that satisfy general acceptance criteria provided by the user and then ranks the records in order of increasing MSE, with the best-matching records having the lowest MSE.

The focus of the DGML is on selecting "as recorded" strong ground motion acceleration time histories for use in seismic analyses. (In fact the records do include the effects of processing by the supplying agency, such as filtering and baseline correction.) Therefore, the tool does not provide the capability of altering the frequency content of the recordings to better match a target spectrum. However, it does provide the ability to linearly scale recorded time histories to improve their match to the target spectrum and select time histories that have the best spectral match. The user has three options for scaling. One option is to apply a scale factor that minimizes the MSE over the period range of interest. This approach results in selection of records that have spectral shapes that are similar on average to the target over the period range of interest, but whose spectra will oscillate about the target. The second option is to scale the records so that the spectral acceleration at a specific period matches the target spectral acceleration at that period. This provides a set of scaled time histories whose spectral accelerations are all equal to the target at the specified period. A third option of not scaling is also available. The choice of scaling approach is up to the user. For all three options, the MSEs of the records are calculated and ranked.

<u>Calculation of MSE.</u> The MSE between the target spectrum and the response spectrum of a recorded time history is computed in terms of the difference in the natural logarithm of spectral acceleration. The period range from 0.01 second to 10 seconds is subdivided into a large number of points equally-spaced in ln (period, T_i) (100 points/log cycle, therefore 301 points from 0.01 second to 10 seconds, end points included) and the target and record response spectra are interpolated to provide spectral accelerations at each period, $SA^{target}(T_i)$, and $SA^{record}(T_i)$, respectively. The MSE is then computed using Equation (1) over periods in the user-specified period range of interest:

$$\text{MSE} = \frac{\sum_{i} w(T_i)\{ln[\text{SA}^{\text{target}}(T_i)] - ln[f \times \text{SA}^{\text{record}}(T_i)]\}^2}{\sum_{i} w(T_i)} \tag{1}$$

Parameter f in Equation (1) is a linear scale factor applied to the entire response spectrum of the recording. Parameter $w(T_i)$ is a weight function that allows the user to assign relative weights to different parts of the period range of interest, providing greater flexibility in the selection of records. The simplest case is to assign equal weight to all periods in the period range of interest (i.e. $w(T_i)$ = 1), but the user may wish to emphasize the match over a narrow period range while maintaining a reasonable match over a broad period range. Arbitrary weight functions may be specified, as described in the Users Manual.

The DGML tool allows the user to select individual component recordings that provide a good match to the target or, alternatively, select recordings for which the geometric mean of the two horizontal components provides a good match to the target spectrum. In this latter case the MSE is computed over both components using Equation (1) with the same value of f applied to both components. This process maintains the relative amplitude of the two horizontal components.

<u>Calculation of the Scale Factor.</u> As discussed above, the user has three options for specifying the scale factor f. The simplest is to use unscaled records, that is f = 1.0. The second approach is to scale the records to match the target spectrum at a specific period, denoted T_s. In this case the scale factor is given by:

$$f = \frac{\text{SA}^{\text{target}}(T_s)}{\text{SA}^{\text{record}}(T_s)} \tag{2}$$

The third option is to apply a scale factor that minimizes the MSE. This approach produces scaled recordings that provide the best match to the spectral shape of the target spectrum over the user-specified period range of interest. Minimization of the MSE as defined in Equation (1) is achieved by a scale factor given by the mean weighted residual in natural logarithm space between the target and the record spectra:

$$ln\, f = \frac{\sum_{i} w(T_i)\, ln\left(\text{SA}^{\text{target}}(T_i) \big/ \text{SA}^{\text{record}}(T_i) \right)}{\sum_{i} w(T_i)} \tag{3}$$

When record selection is based on simultaneously considering both horizontal components, the scale factor computed using Equation (3) minimizes the MSE between the target spectrum and the geometric mean of the spectra for the two horizontal components. The geometric mean (GM) of FN and FP horizontal accelerations is given by:

$$\mathrm{SA}_{GM} = \sqrt{\mathrm{SA}_{FN} \bullet \mathrm{SA}_{FP}} \text{ or } ln\ \mathrm{SA}_{GM} = (ln\,\mathrm{SA}_{FN} + ln\,\mathrm{SA}_{FP})/2 \quad (4)$$

For all three scaling options, the MSE is computed using Equation (1). Note that for all options, it is necessary for the user to specify the weight function because it is used to calculate the MSE and order the results with respect to the degree of match between target spectrum and spectra of recordings over the user-specified period range of significance.

Specification of Search Criteria for Records. The user specifies the ranges of parameters over which searches are to be conducted and other limits and restrictions on the searches These may include: earthquake magnitude range; type of faulting; distance range; V_{S30} range; significant duration range; whether records are to exclude, include, or be limited to pulse records; limits on the scale factor f; and restrictions on directional component (i.e., arbitrary FN or FP components [no restriction]; FN components only; FP component only; or FN and FP components in pair). If three dimensional analyses are to be conducted requiring pairs of horizontal components, ordinarily FN and FP components in pairs would be searched for and scaled by the same factor.

Table 1 summarizes median values of significant duration as defined in Section 2.2 as a function of magnitude, closest source-to-site distance, and V_{S30} (m/sec) that can be used as a guide in specifying duration ranges for searches (if desired) and/or in evaluating durations of selected records. The values in Table 1 are based on Kempton and Stewart (2006). The standard deviation of the natural logarithm of duration obtained by Kempton and Stewart (2006) is 0.44, corresponding to a factor of 1.55 between median estimates and plus-or-minus one standard deviation estimates. Pulse records are discussed in Section 2.4.

Other Criteria. Other criteria to be specified by the user are (1) total number of records for the search that will be displayed in the "ground motion record display window" (see Users Manual); and (2) total number of records for which the average spectrum will be calculated.

2.3.3 Step 3 – Search of Database, Selection of Records, and Saving of Records, Plots and Supporting Information

The software tool scans the database, selects all records meeting user-specified criteria as summarized above, scales records to match the target spectrum, and ranks records in order of increasing MSE. The software tool also has the capability (termed Supplementary Search in the Users Manual) to search for specific records according to specified NGA record sequence number or by earthquake name or recording station name. Selected records from a Supplementary Search are scaled and ranked by MSE and can be incorporated into final data sets as desired by the user. This search capability was added so that users can examine any record or group of records and further fine-tune the search results based on user preferences.

Figure 7 (taken from Figure 24 of the Users Manual) illustrates the DGML graphic interface used to specify primary search criteria and list and plot search results including time histories and individual and average response spectra of scaled records sets compared to a specified design or target spectrum. One-, two-, or three-component time histories of a record can also be viewed at an expanded time scale, if desired to examine details of the time histories, using a feature called "Zoom in Time". The Users Manual describes in detail the procedures for specifying criteria and obtaining and viewing results.

Search Report and Saving of Search Results. For a selected record set, a search report is prepared as described in the Users Manual. The search report includes: search criteria; summary of earthquake, distance, and station/site information; record scaling factors and MSEs; scaled record characteristics including PGA, PGV, PGD, acceleration response spectra, presence of pulses and pulse periods, significant durations, and recommended lowest usable frequencies; and scaled average spectral accelerations for the selected record set along with the target or design spectral accelerations. The search report can be saved as a Windows spread-sheet file. Although the search results are based on horizontal records, the response spectra for corresponding vertical records can also be saved together with their horizontal counterparts in the search report. Spectra and acceleration, velocity, and displacement time history plots can be saved as figure files. The horizontal and/or vertical components of the selected acceleration time histories can also be saved; the saved time histories are the unscaled original data from the PEER NGA database. Therefore, the user can further modify the time histories if required or desired for any purposes (e.g., fine-tune record scaling factors to meet building code requirements for degree of match of an average spectrum of a selected records time history set with a design spectrum; rotate time histories; or adjust match of record spectra to a design spectrum through frequency content altering methods.).

2.4 SUPPLEMENTAL INFORMATION ABOUT FORMING RECORDS SETS CONTAINING RECORDS WITH PULSES

Within the NGA database, ground motion records have been identified as having strong velocity pulses that may be associated with fault rupture directivity effects. Prior research (Somerville et al., 1997) has indicated that the strongest pulses are generally more closely aligned with the FN direction than the FP direction. As discussed previously, the time history records in the DGML have been rotated into FN and FP directions and their response spectra calculated for these directions.

2.4.1 Database for Records With Pulses

The principal resource used in identifying and characterizing records with velocity pulses for the DGML has been the research by Baker (2007). Baker analyzed all records within the NGA database and identified FN records having strong velocity pulses that may be associated with rupture directivity effects. The basic approach followed by Baker was to use wavelet analysis to identify the largest velocity pulses. General criteria that were used in defining records with pulses were (1) the pulse is large relative to the residual features of the ground motion after the pulse is extracted, (2) the pulse arrives early in the time history, as would be expected for pulses associated with rupture directivity effects, and (3) the absolute velocity amplitudes are large (PGV of record equal to or greater than 30 cm/sec). The detailed criteria and results for the FN components are described by Baker (2007). The same criteria were applied by Baker for the FP component and those results as well as more detailed results and documentation of analyses for both components are contained on the website http://www.stanford.edu/~bakerjw/pulse-classification.html. Note that there can be no assurance that velocity pulses of records in the database are due to directivity effects without more detailed seismological study of individual records. It is likely that other seismological factors may have caused or contributed to the velocity pulses of some records. However, while the causative mechanisms for the pulses are uncertain, it is expected that the pulses are similar to those caused by directivity and therefore suitable for use in modeling effects of directivity pulses on structures.

Somerville (2003), Mavroeidis and Papageorgiou (2003), Bray and Rodriguez-Marek (2004), and Fu and Menon (2004) also prepared lists of near-fault records considered to have strong ground motion pulses. The focus of these researchers was on identifying pulses on the FN components and only a few FP pulse records were identified. From examination of these data sets, several additional records having FN pulses were identified. In determining the additional records, we used the criteria that PGV for the records was equal to or greater than 30 cm/sec (same as Baker's criterion) and the records had been identified as pulse records in at least two studies.

Pulse records have been identified in the DGML database as follows: Sixty records having pulses for the FN components only; nineteen records having pulses in the FP components only; and thirty records having pulses in both FN and FP components. Several of the records originally identified as having pulses are not part of the DGML database because they are among the records listed in Table B-2 of Appendix B as being excluded from the DGML for various reasons.

Tables 2a and 2b summarize information about individual FN and FP pulse records, respectively, including NGA record no., earthquake name, year, magnitude, and type of faulting (mechanism), recording station name, earthquake source-to-site distance, Vs30 of geologic deposits at recording station sites, and estimates of pulse periods and significant durations for the records. The distribution of the identified pulse records by earthquake magnitude, type of faulting, and source-to-site distance is shown in Tables 3a and 3b for FN and FP pulse records, respectively. Tables 3a and 3b indicate that the great majority of pulse records are located within 20 km from the source, and, of these, most are within 10 km. There are relatively very few pulse records beyond 30 km.

Estimates of pulse periods shown in Tables 2a and 2b were taken from Baker (2007) and the website http://www.stanford.edu/~bakerjw/pulse-classification.html except for a few records added to Baker's compilation. We compared estimates of FN pulse periods for 28 records where they had been identified in Baker (2007) and at least in two of other studies (Somerville, 2003, Mavroeidis and Papageorgiou, 2003, Bray and Rodriguez-Marek, 2004, Fu and Menun, 2004). For 23 records, the total range in estimated pulse periods among researchers was a factor of 1.4 or less and for 15 of these records was within a factor of 1.2. For the remaining 5 records, estimated pulse periods had greater divergence and varied up to a factor of 5.

All of the researchers mentioned above found a trend for pulse period to increase with magnitude, and this trend is expected based on the physics of fault rupture (Somerville, 2003). Figure 8 shows the individual record estimates of FN pulse period and the mean correlation between pulse period and magnitude of Baker (2007). Although the correlation for pulse period to increase with magnitude is clear, considerable data scatter can also be noted. The standard deviation of the natural logarithm of pulse period determined from Baker's regression was 0.55, corresponding to a factor of about 1.7 between the median regression estimates and median-plus-or-minus one standard deviation estimates. Figure 9 shows mean correlations of pulse period with magnitude by different investigators. All the correlations show a similar trend for pulse period to increase with magnitude.

2.4.2 Selecting Records with Pulses Within the DGML

If desired, a user of the DGML can limit searches of records to those having pulses through options available on the user interface. Searches can be made for records having FN pulses, FP pulses, or both FN and FP pulses. Similar to other searches for records in the DGML, a user can specify criteria and limits described in Section 2.3.2 in searches for pulse records. Pulse records can be scaled and ranked for spectral match as described in Section 2.3.

It is thought that the effects of type of faulting on pulse period may be significant for large magnitude earthquakes, although the effect is not well defined. Therefore it is suggested that for earthquakes greater than magnitude 6.5, records from strike-slip earthquakes not be used for reverse-slip or normal-slip earthquakes and visa versa. Few pulse records from normal-slip earthquakes are in the database, and records from reverse-slip earthquakes are suggested to be used for normal slip earthquakes. In order to obtain a more detailed understanding of the nature of pulses in time history records considered for analysis, it is suggested that the velocity time histories of candidate time histories be displayed and examined. This can be readily done through the DGML graphic interface.

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TABLES

TABLE 1

SIGNIFICANT DURATION OF SHAKING BASED ON KEMPTON AND STEWART (2006)

R (km)	Vs30 (m/sec)	Median Duration (sec)*						
		M = 5	M = 5.5	M = 6	M = 6.5	M = 7	M = 7.5	M = 8
0	760	1.6	2.6	4.1	6.4	10.0	15.5	24.1
	520	2.4	3.3	4.8	7.1	10.7	16.2	24.8
	250	3.2	4.2	5.6	7.9	11.5	17.0	25.6
10	760	3.2	4.3	6.0	8.7	12.9	19.3	29.3
	520	4.1	5.2	6.9	9.6	13.7	20.1	30.1
	250	5.0	6.1	7.8	10.5	14.7	21.1	31.1
20	760	5.2	6.5	8.5	11.6	16.4	23.9	35.5
	520	6.2	7.5	9.5	12.6	17.4	24.9	36.5
	250	7.3	8.6	10.6	13.7	18.5	26.0	37.6
50	760	9.7	11.0	13.0	16.1	20.9	28.4	40.0
	520	10.7	12.0	14.0	17.1	21.9	29.4	41.0
	250	11.8	13.1	15.1	18.2	23.0	30.5	42.1
100	760	17.2	18.5	20.5	23.6	28.4	35.9	47.5
	520	18.2	19.5	21.5	24.6	29.4	36.9	48.5
	250	19.3	20.6	22.6	25.7	30.5	38.0	49.6
200	760	32.2	33.5	35.5	38.6	43.4	50.9	62.5
	520	33.2	34.5	36.5	39.6	44.4	51.9	63.5
	250	34.3	35.6	37.6	40.7	45.5	53.0	64.6

* Significant duration is defined as the time required to build up from 5% to 95% of the Arias Intensity of an acceleration time history.

TABLE 2a

FAULT-NORMAL PULSELIKE GROUND MOTION RECORDS IN DGML

NGA#	Comp.	Event	Year	Station	Tp	Mag	Mechanism	Rjb* (km)	Rrup* (km)	Vs30** (m/s)	Duration (sec)
77	FN	San Fernando	1971	Pacoima Dam (upper left abut)	1.6	6.6	Reverse	0.0	1.8	2016	7.1
150	FN	Coyote Lake	1979	Gilroy Array #6	1.2	5.7	Strike-Slip	0.4	3.1	663	3.4
158	FN	Imperial Valley-06	1979	Aeropuerto Mexicali	2.4	6.5	Strike-Slip	0.0	0.3	275	7.1
159	FN	Imperial Valley-06	1979	Agrarias	2.3	6.5	Strike-Slip	0.0	0.7	275	11.5
161	FN	Imperial Valley-06	1979	Brawley Airport	4.0	6.5	Strike-Slip	8.5	10.4	209	15.2
170	FN	Imperial Valley-06	1979	EC County Center FF	4.5	6.5	Strike-Slip	7.3	7.3	192	14.9
171	FN	Imperial Valley-06	1979	EC Meloland Overpass FF	3.3	6.5	Strike-Slip	0.1	0.1	186	6.2
173	FN	Imperial Valley-06	1979	El Centro Array #10	4.5	6.5	Strike-Slip	6.2	6.2	203	13.0
174	FN	Imperial Valley-06	1979	El Centro Array #11	7.4	6.5	Strike-Slip	12.5	12.5	196	8.3
178	FN	Imperial Valley-06	1979	El Centro Array #3	5.2	6.5	Strike-Slip	10.8	12.9	163	14.2
179	FN	Imperial Valley-06	1979	El Centro Array #4	4.6	6.5	Strike-Slip	4.9	7.1	209	10.2
180	FN	Imperial Valley-06	1979	El Centro Array #5	4.0	6.5	Strike-Slip	1.8	4.0	206	9.4
181	FN	Imperial Valley-06	1979	El Centro Array #6	3.8	6.5	Strike-Slip	0.0	1.4	203	8.5
182	FN	Imperial Valley-06	1979	El Centro Array #7	4.2	6.5	Strike-Slip	0.6	0.6	211	4.8
183	FN	Imperial Valley-06	1979	El Centro Array #8	5.4	6.5	Strike-Slip	3.9	3.9	206	5.8
184	FN	Imperial Valley-06	1979	El Centro Differential Array	5.9	6.5	Strike-Slip	5.1	5.1	202	6.9
185	FN	Imperial Valley-06	1979	Holtville Post Office	4.8	6.5	Strike-Slip	5.5	7.7	203	11.8
250	FN	Mammoth Lakes-06	1980	Long Valley Dam (Upr L Abut)	1.1	5.9	Strike-Slip	9.3	16.2	345	7.2
292	FN	Irpinia, Italy-01	1980	Sturno	3.1	6.9	Normal	6.8	10.8	1000	16.7
316	FN	Westmorland	1981	Parachute Test Site	3.6	5.9	Strike-Slip	16.5	16.7	349	17.3
407	FN	Coalinga-05	1983	Oil City	0.7	5.8	Reverse	2.4	8.5	376	2.8
415	FN	Coalinga-05	1983	Transmitter Hill	0.9	5.8	Reverse	4.1	9.5	376	3.9
418	FN	Coalinga-07	1983	Coalinga-14th & Elm (Old CHP)	0.4	5.2	Reverse	7.6	11.0	339	0.7
451	FN	Morgan Hill	1984	Coyote Lake Dam (SW Abut)	1.0	6.2	Strike-Slip	0.2	0.5	597	3.1
459	FN	Morgan Hill	1984	Gilroy Array #6	1.2	6.2	Strike-Slip	9.9	9.9	663	6.9
529	FN	N. Palm Springs	1986	North Palm Springs	1.4	6.1	Reverse-Oblique	0.0	4.0	345	4.5
568	FN	San Salvador	1986	Geotech Investig Center	0.9	5.8	Strike-Slip	2.1	6.3	545	3.8
615	FN	Whittier Narrows-01	1987	Downey - Co Maint Bldg	0.8	6.0	Reverse-Oblique	15.0	20.8	272	8.3
645	FN	Whittier Narrows-01	1987	LB - Orange Ave	1.0	6.0	Reverse-Oblique	19.8	24.5	270	8.3
721	FN	Superstition Hills-02	1987	El Centro Imp. Co. Cent	2.4	6.5	Strike-Slip	18.2	18.2	192	18.8
723	FN	Superstition Hills-02	1987	Parachute Test Site	2.3	6.5	Strike-Slip	1.0	1.0	349	10.5
738	FN	Loma Prieta	1989	Alameda Naval Air Stn Hanger	2.0	6.9	Reverse-Oblique	70.9	71.0	190	6.0
763	FN	Loma Prieta	1989	Gilroy - Gavilan Coll.	1.8	6.9	Reverse-Oblique	9.2	10.0	730	5.2

TABLE 2a

FAULT-NORMAL PULSELIKE GROUND MOTION RECORDS IN DGML

NGA#	Comp.	Event	Year	Station	Tp	Mag	Mechanism	Rjb* (km)	Rrup* (km)	Vs30** (m/s)	Duration (sec)
765	FN	Loma Prieta	1989	Gilroy Array #1	1.2	6.9	Reverse-Oblique	8.8	9.6	1428	5.1
766	FN	Loma Prieta	1989	Gilroy Array #2	1.7	6.9	Reverse-Oblique	10.4	11.1	271	10.1
767	FN	Loma Prieta	1989	Gilroy Array #3	1.5	6.9	Reverse-Oblique	12.2	12.8	350	7.7
779	FN	Loma Prieta	1989	LGPC	3.0	6.9	Reverse-Oblique	0.0	3.9	478	10.0
783	FN	Loma Prieta	1989	Oakland - Outer Harbor Wharf	1.8	6.9	Reverse-Oblique	74.2	74.3	249	6.0
802	FN	Loma Prieta	1989	Saratoga - Aloha Ave	4.5	6.9	Reverse-Oblique	7.6	8.5	371	8.4
803	FN	Loma Prieta	1989	Saratoga - W Valley Coll.	1.9	6.9	Reverse-Oblique	8.5	9.3	371	11.0
821	FN	Erzican, Turkey	1992	Erzincan	2.7	6.7	Strike-Slip	0.0	4.4	275	6.9
828	FN	Cape Mendocino	1992	Petrolia	3.0	7.0	Reverse	0.0	8.2	713	16.2
838	FN	Landers	1992	Barstow	8.9	7.3	Strike-Slip	34.9	34.9	371	17.4
879	FN	Landers	1992	Lucerne	5.1	7.3	Strike-Slip	2.2	2.2	685	12.9
900	FN	Landers	1992	Yermo Fire Station	7.5	7.3	Strike-Slip	23.6	23.6	354	17.2
1013	FN	Northridge-01	1994	LA Dam	1.7	6.7	Reverse	0.0	5.9	629	6.5
1044	FN	Northridge-01	1994	Newhall - Fire Sta	2.2	6.7	Reverse	3.2	5.9	269	5.5
1045	FN	Northridge-01	1994	Newhall - W Pico Canyon Rd.	2.4	6.7	Reverse	2.1	5.5	286	7.1
1050	FN	Northridge-01	1994	Pacoima Dam (downstr)	0.5	6.7	Reverse	4.9	7.0	2016	3.8
1051	FN	Northridge-01	1994	Pacoima Dam (upper left)	0.9	6.7	Reverse	4.9	7.0	2016	6.0
1063	FN	Northridge-01	1994	Rinaldi Receiving Sta	1.2	6.7	Reverse	0.0	6.5	282	7.1
1084	FN	Northridge-01	1994	Sylmar - Converter Sta	3.5	6.7	Reverse	0.0	5.4	251	13.5
1085	FN	Northridge-01	1994	Sylmar - Converter Sta East	3.5	6.7	Reverse	0.0	5.2	371	7.2
1086	FN	Northridge-01	1994	Sylmar - Olive View Med FF	3.1	6.7	Reverse	1.7	5.3	441	5.8
1106	FN	Kobe, Japan	1995	KJMA	1.0	6.9	Strike-Slip	0.9	1.0	312	9.6
1119	FN	Kobe, Japan	1995	Takarazuka	1.4	6.9	Strike-Slip	0.0	0.3	312	5.1
1120	FN	Kobe, Japan	1995	Takatori	1.6	6.9	Strike-Slip	1.5	1.5	256	10.8
1176	FN	Kocaeli, Turkey	1999	Yarimca	4.5	7.5	Strike-Slip	1.4	4.8	297	15.4
1202	FN	Chi-Chi, Taiwan	1999	CHY035	1.4	7.6	Reverse-Oblique	12.6	12.7	[555]	28.1
1244	FN	Chi-Chi, Taiwan	1999	CHY101	4.8	7.6	Reverse-Oblique	10.0	10.0	259	29.1
1476	FN	Chi-Chi, Taiwan	1999	TCU029	6.4	7.6	Reverse-Oblique	28.1	28.1	[426]	19.2
1477	FN	Chi-Chi, Taiwan	1999	TCU031	6.2	7.6	Reverse-Oblique	30.2	30.2	489	24.1
1479	FN	Chi-Chi, Taiwan	1999	TCU034	8.6	7.6	Reverse-Oblique	35.7	35.7	394	19.3
1480	FN	Chi-Chi, Taiwan	1999	TCU036	5.4	7.6	Reverse-Oblique	19.8	19.8	[495]	22.9
1481	FN	Chi-Chi, Taiwan	1999	TCU038	7.0	7.6	Reverse-Oblique	25.4	25.4	[229]	27.6
1483	FN	Chi-Chi, Taiwan	1999	TCU040	6.3	7.6	Reverse-Oblique	22.1	22.1	362	25.2

TABLE 2a

FAULT-NORMAL PULSELIKE GROUND MOTION RECORDS IN DGML

NGA#	Comp.	Event	Year	Station	Tp	Mag	Mechanism	Rjb* (km)	Rrup* (km)	Vs30** (m/s)	Duration (sec)
1484	FN	Chi-Chi, Taiwan	1999	TCU042	9.1	7.6	Reverse-Oblique	26.3	26.3	[424]	18.5
1486	FN	Chi-Chi, Taiwan	1999	TCU046	8.6	7.6	Reverse-Oblique	16.7	16.7	466	18.5
1492	FN	Chi-Chi, Taiwan	1999	TCU052	8.5	7.6	Reverse-Oblique	0.0	0.7	579	16.2
1493	FN	Chi-Chi, Taiwan	1999	TCU053	13.0	7.6	Reverse-Oblique	6.0	6.0	455	22.1
1494	FN	Chi-Chi, Taiwan	1999	TCU054	10.0	7.6	Reverse-Oblique	5.3	5.3	461	22.9
1496	FN	Chi-Chi, Taiwan	1999	TCU056	13.0	7.6	Reverse-Oblique	10.5	10.5	[440]	26.7
1499	FN	Chi-Chi, Taiwan	1999	TCU060	12.0	7.6	Reverse-Oblique	8.5	8.5	[496]	21.1
1503	FN	Chi-Chi, Taiwan	1999	TCU065	5.7	7.6	Reverse-Oblique	0.6	0.6	306	28.2
1505	FN	Chi-Chi, Taiwan	1999	TCU068	12.0	7.6	Reverse-Oblique	0.0	0.3	487	12.5
1510	FN	Chi-Chi, Taiwan	1999	TCU075	5.1	7.6	Reverse-Oblique	0.9	0.9	573	27.0
1511	FN	Chi-Chi, Taiwan	1999	TCU076	4.0	7.6	Reverse-Oblique	2.8	2.8	615	29.5
1515	FN	Chi-Chi, Taiwan	1999	TCU082	9.2	7.6	Reverse-Oblique	5.2	5.2	473	22.6
1519	FN	Chi-Chi, Taiwan	1999	TCU087	9.0	7.6	Reverse-Oblique	7.0	7.0	[562]	21.8
1526	FN	Chi-Chi, Taiwan	1999	TCU098	7.5	7.6	Reverse-Oblique	47.7	47.7	[230]	33.2
1529	FN	Chi-Chi, Taiwan	1999	TCU102	9.7	7.6	Reverse-Oblique	1.5	1.5	714	16.4
1530	FN	Chi-Chi, Taiwan	1999	TCU103	8.3	7.6	Reverse-Oblique	6.1	6.1	494	20.9
1531	FN	Chi-Chi, Taiwan	1999	TCU104	12.0	7.6	Reverse-Oblique	12.9	12.9	[544]	28.7
1548	FN	Chi-Chi, Taiwan	1999	TCU128	9.0	7.6	Reverse-Oblique	13.2	13.2	600	20.7
1550	FN	Chi-Chi, Taiwan	1999	TCU136	10.0	7.6	Reverse-Oblique	8.3	8.3	[538]	19.8
1853	FN	Yountville	2000	Napa Fire Station #3	0.7	5.0	Strike-Slip	8.4	11.5	271	3.3
2457	FN	Chi-Chi, Taiwan-03	1999	CHY024	3.2	6.2	Reverse	18.5	19.7	428	8.6
2495	FN	Chi-Chi, Taiwan-03	1999	CHY080	1.4	6.2	Reverse	21.3	22.4	[680]	2.9
2627	FN	Chi-Chi, Taiwan-03	1999	TCU076	0.9	6.2	Reverse	13.0	14.7	615	3.0
3317	FN	Chi-Chi, Taiwan-06	1999	CHY101	2.8	6.3	Reverse	34.6	36.0	259	18.4

Notes:

* Joyner-Boore distance (Rjb) and closest distance (Rrup) for earthquakes not having fault rupture models are shown in red; distances were estimated using epicentral and hypocentral distances and simulations (Chiou and Youngs, 2008b).

** Updated preferred Vs30 values for CWB Taiwan sites are shown in brackets; values were estimated by B. Chiou (2009, personal communication).

TABLE 2b

FAULT-PARALLEL PULSELIKE GROUND MOTION RECORDS IN DGML

NGA#	Comp.	Event	Year	Station	Tp	Mag	Mechanism	Rjb (km)	Rrup (km)	Vs30** (m/s)	Duration (sec)
173	FP	Imperial Valley-06	1979	El Centro Array #10	2.0	6.5	Strike-Slip	6.2	6.2	203	11.9
178	FP	Imperial Valley-06	1979	El Centro Array #3	3.1	6.5	Strike-Slip	10.8	12.9	163	11.9
181	FP	Imperial Valley-06	1979	El Centro Array #6	2.6	6.5	Strike-Slip	0.0	1.4	203	11.4
182	FP	Imperial Valley-06	1979	El Centro Array #7	4.5	6.5	Strike-Slip	0.6	0.6	211	6.8
184	FP	Imperial Valley-06	1979	El Centro Differential Array	2.0	6.5	Strike-Slip	5.1	5.1	202	6.4
185	FP	Imperial Valley-06	1979	Holtville Post Office	3.6	6.5	Strike-Slip	5.5	7.7	203	12.7
292	FP	Irpinia, Italy-01	1980	Sturno	3.5	6.9	Normal	6.8	10.8	1000	12.1
316	FP	Westmorland	1981	Parachute Test Site	4.2	5.9	Strike-Slip	16.5	16.7	349	15.5
319	FP	Westmorland	1981	Westmorland Fire Sta	1.4	5.9	Strike-Slip	6.2	6.5	194	6.1
451	FP	Morgan Hill	1984	Coyote Lake Dam (SW Abut)	1.1	6.2	Strike-Slip	0.2	0.5	597	5.4
496	FP	Nahanni, Canada	1985	Site 2	0.8	6.8	Reverse	0.0	4.9	660	9.1
568	FP	San Salvador	1986	Geotech Investig Center	1.8	5.8	Strike-Slip	2.1	6.3	545	4.2
569	FP	San Salvador	1986	National Geografical Inst	1.0	5.8	Strike-Slip	3.7	7.0	350	4.6
722	FP	Superstition Hills-02	1987	Kornbloom Road (temp)	2.1	6.5	Strike-Slip	18.5	18.5	207	13.4
738	FP	Loma Prieta	1989	Alameda Naval Air Stn Hanger	2.3	6.9	Reverse-Oblique	70.9	71.0	190	4.6
764	FP	Loma Prieta	1989	Gilroy - Historic Bldg.	1.8	6.9	Reverse-Oblique	10.3	11.0	339	9.8
767	FP	Loma Prieta	1989	Gilroy Array #3	3.0	6.9	Reverse-Oblique	12.2	12.8	350	8.9
779	FP	Loma Prieta	1989	LGPC	4.1	6.9	Reverse-Oblique	0.0	3.9	478	10.9
784	FP	Loma Prieta	1989	Oakland - Title & Trust	1.7	6.9	Reverse-Oblique	72.1	72.2	306	13.3
803	FP	Loma Prieta	1989	Saratoga - W Valley Coll.	5.0	6.9	Reverse-Oblique	8.5	9.3	371	12.4
821	FP	Erzican, Turkey	1992	Erzincan	2.2	6.7	Strike-Slip	0.0	4.4	275	10.0
825	FP	Cape Mendocino	1992	Cape Mendocino	4.9	7.0	Reverse	0.0	7.0	514	6.5
828	FP	Cape Mendocino	1992	Petrolia	1.0	7.0	Reverse	0.0	8.2	713	17.3
1013	FP	Northridge-01	1994	LA Dam	2.8	6.7	Reverse	0.0	5.9	629	6.5
1045	FP	Northridge-01	1994	Newhall - W Pico Canyon Rd.	2.2	6.7	Reverse	2.1	5.5	286	9.0
1063	FP	Northridge-01	1994	Rinaldi Receiving Sta	3.0	6.7	Reverse	0.0	6.5	282	10.1
1176	FP	Kocaeli, Turkey	1999	Yarimca	4.6	7.5	Strike-Slip	1.4	4.8	297	14.9
1193	FP	Chi-Chi, Taiwan	1999	CHY024	6.2	7.6	Reverse-Oblique	9.6	9.6	428	26.9
1463	FP	Chi-Chi, Taiwan	1999	TCU003	11.0	7.6	Reverse-Oblique	86.6	86.6	517	41.3
1468	FP	Chi-Chi, Taiwan	1999	TCU010	11.0	7.6	Reverse-Oblique	82.2	82.3	[484]	37.6
1475	FP	Chi-Chi, Taiwan	1999	TCU026	9.3	7.6	Reverse-Oblique	56.0	56.1	[488]	22.1
1477	FP	Chi-Chi, Taiwan	1999	TCU031	11.0	7.6	Reverse-Oblique	30.2	30.2	489	33.7

TABLE 2b

FAULT-PARALLEL PULSELIKE GROUND MOTION RECORDS IN DGML

NGA#	Comp.	Event	Year	Station	Tp	Mag	Mechanism	Rjb (km)	Rrup (km)	Vs30** (m/s)	Duration (sec)
1480	FP	Chi-Chi, Taiwan	1999	TCU036	6.4	7.6	Reverse-Oblique	19.8	19.8	[495]	27.5
1481	FP	Chi-Chi, Taiwan	1999	TCU038	7.8	7.6	Reverse-Oblique	25.4	25.4	[229]	25.7
1482	FP	Chi-Chi, Taiwan	1999	TCU039	8.1	7.6	Reverse-Oblique	19.9	19.9	541	26.7
1483	FP	Chi-Chi, Taiwan	1999	TCU040	7.9	7.6	Reverse-Oblique	22.1	22.1	362	29.3
1498	FP	Chi-Chi, Taiwan	1999	TCU059	7.6	7.6	Reverse-Oblique	17.1	17.1	[230]	32.3
1501	FP	Chi-Chi, Taiwan	1999	TCU063	5.1	7.6	Reverse-Oblique	9.8	9.8	476	31.7
1502	FP	Chi-Chi, Taiwan	1999	TCU064	8.7	7.6	Reverse-Oblique	16.6	16.6	[358]	28.4
1505	FP	Chi-Chi, Taiwan	1999	TCU068	11.0	7.6	Reverse-Oblique	0.0	0.3	487	13.1
1523	FP	Chi-Chi, Taiwan	1999	TCU094	9.1	7.6	Reverse-Oblique	54.5	54.5	590	25.5
1525	FP	Chi-Chi, Taiwan	1999	TCU096	8.3	7.6	Reverse-Oblique	54.5	54.5	[421]	29.1
1526	FP	Chi-Chi, Taiwan	1999	TCU098	8.3	7.6	Reverse-Oblique	47.7	47.7	[230]	27.8
1529	FP	Chi-Chi, Taiwan	1999	TCU102	3.8	7.6	Reverse-Oblique	1.5	1.5	714	18.9
1531	FP	Chi-Chi, Taiwan	1999	TCU104	7.3	7.6	Reverse-Oblique	12.9	12.9	[544]	29.3
1548	FP	Chi-Chi, Taiwan	1999	TCU128	10.0	7.6	Reverse-Oblique	13.2	13.2	600	19.6
1550	FP	Chi-Chi, Taiwan	1999	TCU136	7.9	7.6	Reverse-Oblique	8.3	8.3	[538]	24.1
1605	FP	Duzce, Turkey	1999	Duzce	5.6	7.1	Strike-Slip	0.0	6.6	276	10.7
3475	FP	Chi-Chi, Taiwan-06	1999	TCU080	1.0	6.3	Reverse	0.0	10.2	[509]	6.8

Notes:

** Updated preferred Vs30 values for CWB Taiwan sites are shown in brackets; values were estimated by B. Chiou (2009, personal communication).

TABLE 3

MAGNITUDE-DISTANCE DISTRIBUTION OF PULSELIKE RECORDS

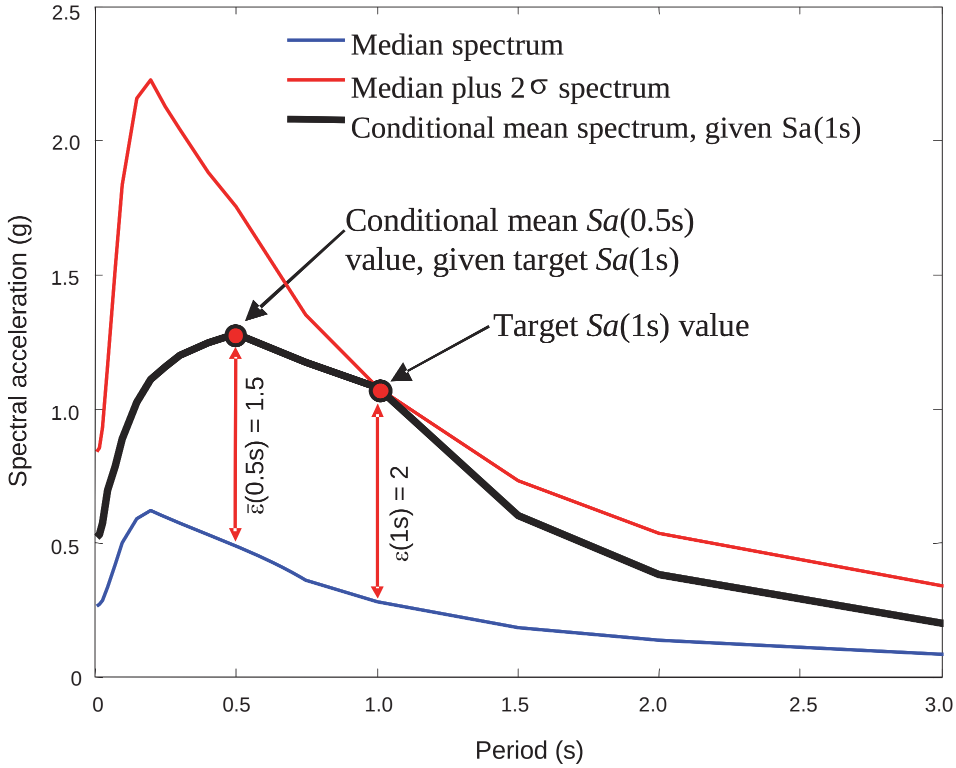
(3a) FAULT-NORMAL

FN	Rrup	0~10 km			10~20 km			20~30 km			30~50 km			> 50 km			sum
Mag		SS	NOR	REV	SS	NOR	REV	SS	NOR	REV	SS	NOR	REV	SS	NOR	REV	
5~6		2	0	2	3	0	1	0	0	2	0	0	0	0	0	0	10
6~7		19	0	16	4	1	4	0	0	1	0	0	1	0	0	2	48
7~8		2	0	15	0	0	6	1	0	4	1	0	3	0	0	0	32
sum		56			19			8			5			2			90

(3b) FAULT-PARALLEL

FN	Rrup	0~10 km			10~20 km			20~30 km			30~50 km			> 50 km			sum
Mag		SS	NOR	REV	SS	NOR	REV	SS	NOR	REV	SS	NOR	REV	SS	NOR	REV	
5~6		3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	4
6~7		7	0	6	2	1	3	0	0	0	0	0	0	0	0	2	21
7~8		2	0	7	0	0	6	0	0	2	0	0	2	0	0	5	24
sum		25			13			2			2			7			49

FIGURES



a) Illustration of conditional mean spectrum (from Baker 2006)

1. Compute the mean and standard deviation of logarithmic spectral acceleration at all periods for a target magnitude and distance

$$\overline{\ln Sa}(M, R, T)$$

$$\sigma_{\ln Sa}(T)$$

2. Compute the target ε at T_1 (from disaggregation or back-calculation)
(Note: T_1 is shown at 1.0-second period for the example in part (a).)

$$\varepsilon(T_1) = \frac{\ln Sa(T_1)^* - \overline{\ln Sa}(M, R, T_1)}{\sigma_{\ln Sa}(T_1)}$$

3. Compute the conditional mean ε at other periods, given $\varepsilon(T_1)$

$$\bar{\varepsilon}(T_2) = \rho \cdot \varepsilon(T_1)$$

for which updated equations for the correlation coefficient, ρ, for NGA models are given by Baker and Jayaram (2008).

4. Compute the spectral acceleration at all periods, using this information

$$\ln Sa(T_2)^* = \overline{\ln Sa}(M, R, T_2) + \sigma_{\ln Sa}(T_2) \cdot \bar{\varepsilon}(T_2)$$

b) Steps in calculating conditional mean spectrum (modified from Baker 2006)

Figure 1
Illustration and calculation of a conditional mean spectrum

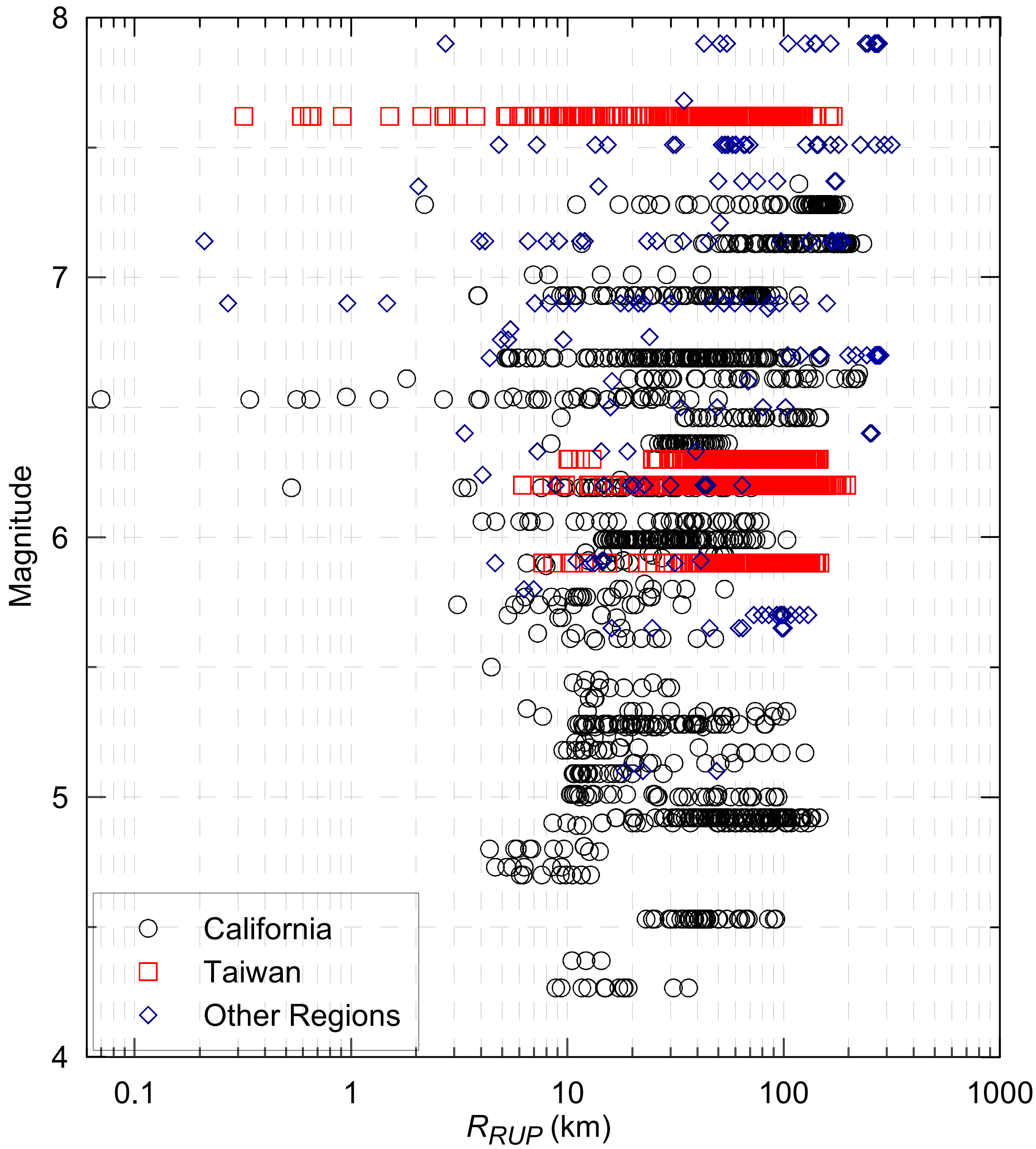
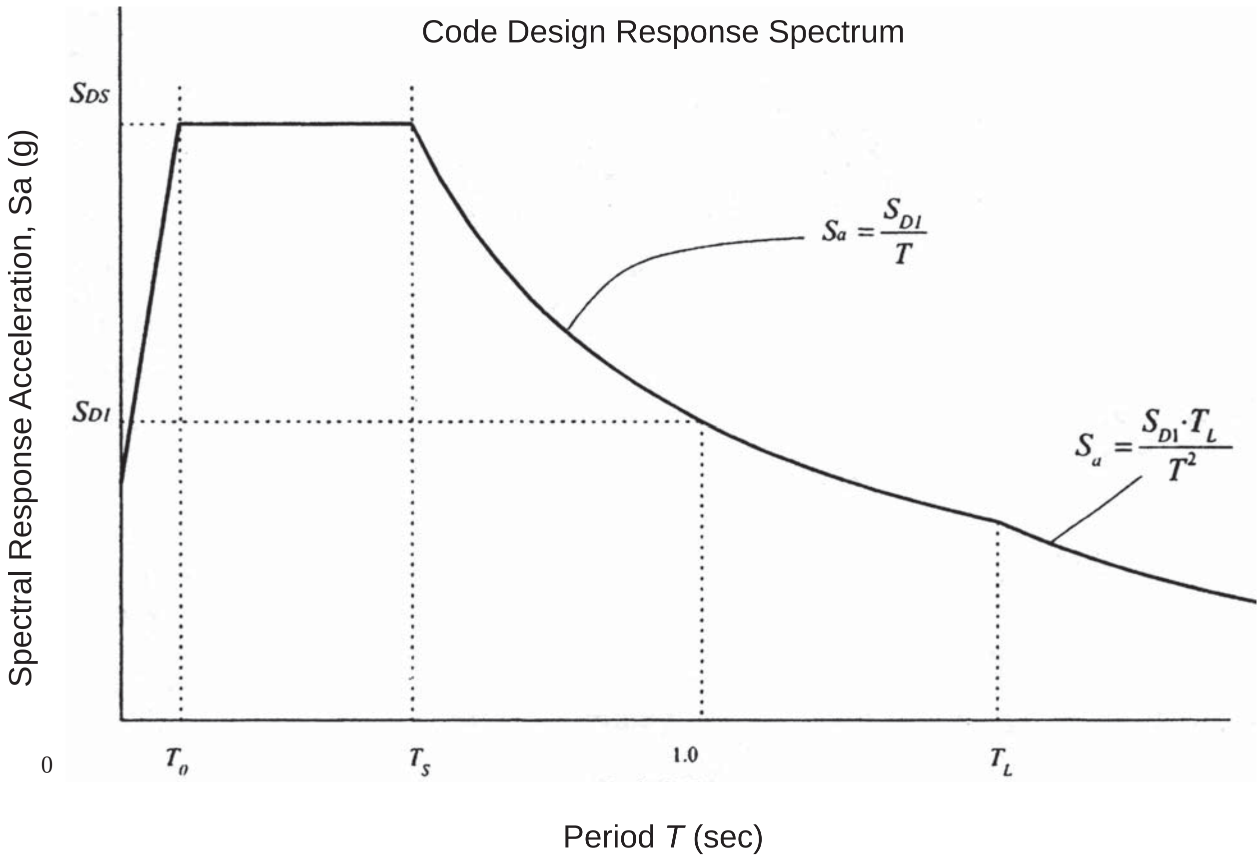


Figure 2

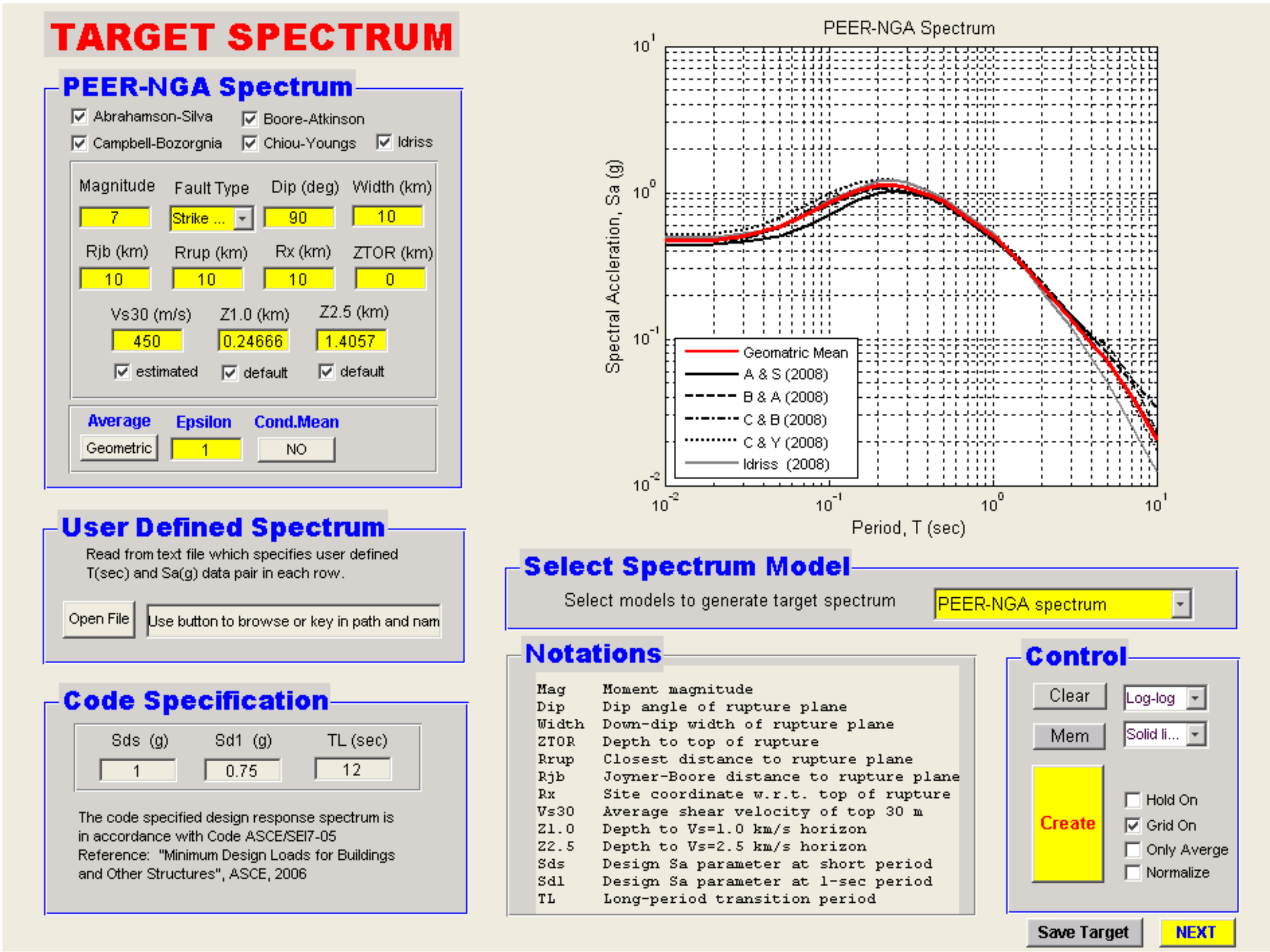
Magnitude and distance distribution for PEER NGA records in DGML database



Notes:

1. Definitions of all parameters and equations for construction of the design response spectrum are given in the 2003 NEHRP Provisions, ASCE Standard 7-05, and 2006 International Building Code.
2. For construction of the code design response spectrum by the DGML software tool, the user specifies parameters S_{DS}, S_{D1}, and T_L.
3. The maximum considered earthquake (MCE) response spectrum is equal to 1.5 times the design response spectrum.

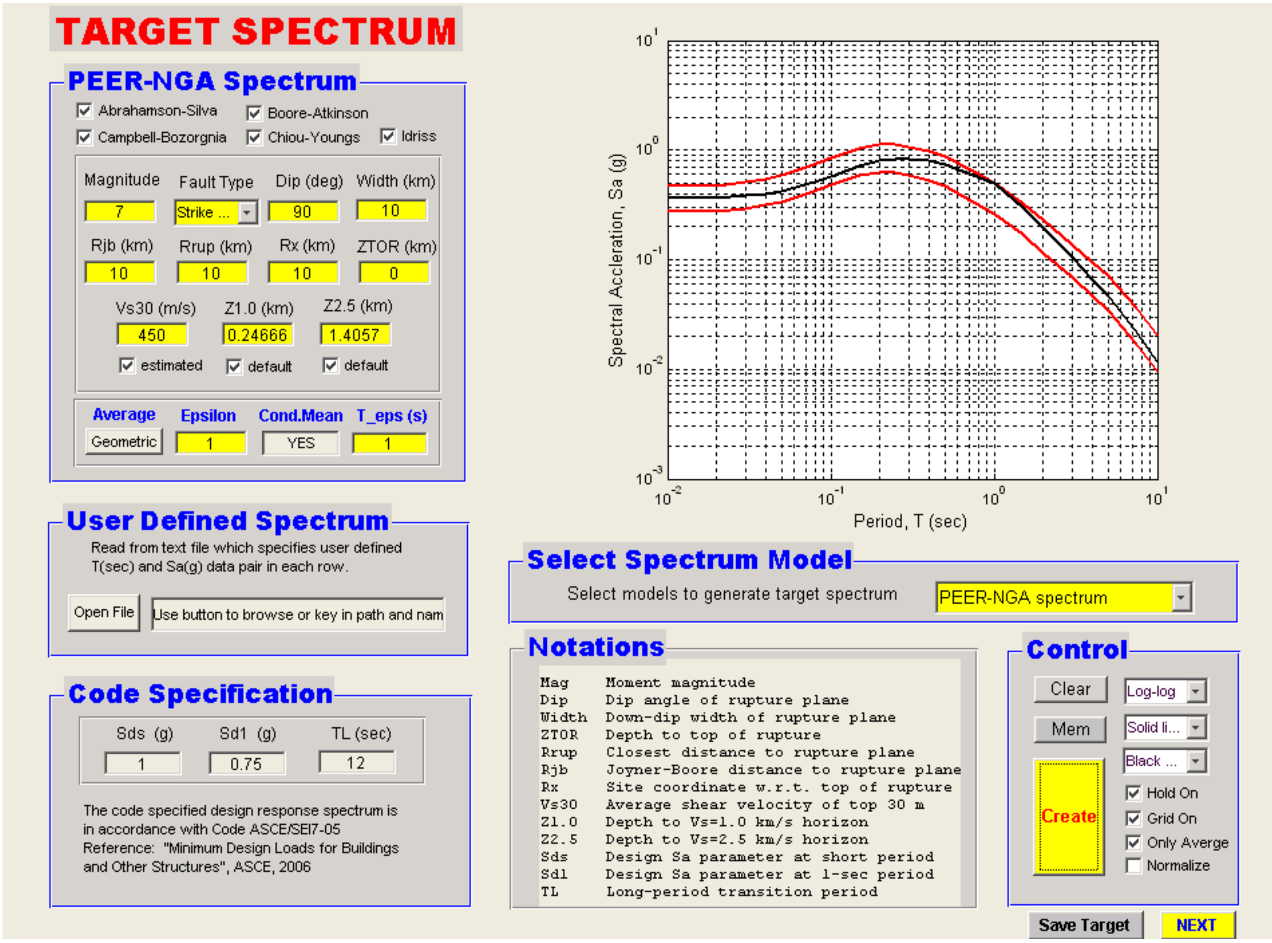
Figure 3
Code response spectrum



Note:

Response spectra are constructed at 1ε (one-standard-deviation) level for this example.

Figure 4
Example of individual and average NGA response spectra from five models constructed by DGML software tool.



Note:

The lower and upper red curves are median and 1ε NGA response spectra (average of five NGA models). Black curve is conditional mean response spectrum -- conditional on spectral acceleration at 1-second period being at the 1ε level for this example.

Figure 5
Example of conditional mean NGA response spectrum constructed by DGML software tool.

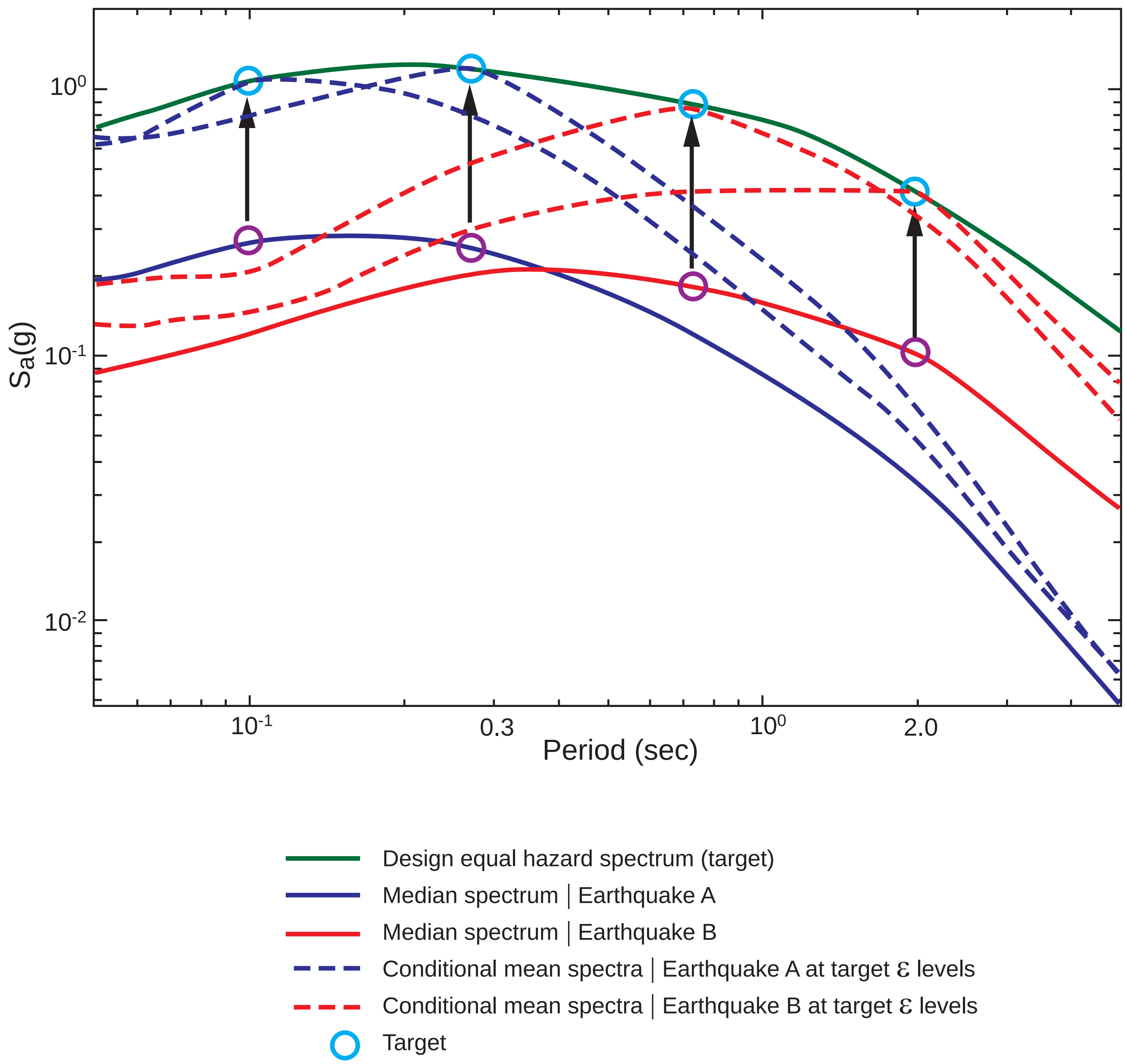


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Figure 6

Illustration of construction of conditional mean spectra for different periods for multiple scenario earthquakes (based on Cornell 2006)

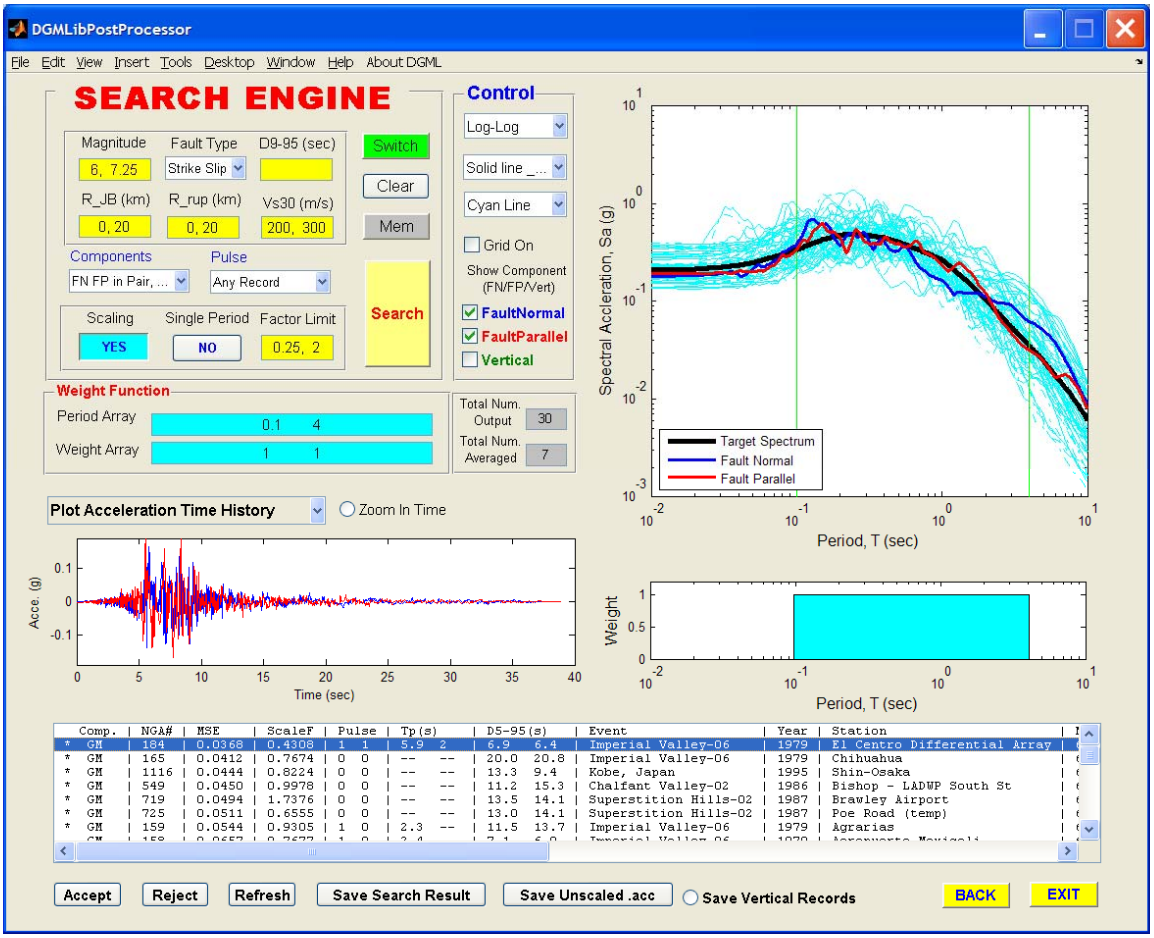

Figure 7
Example of record search performed by DGML software tool

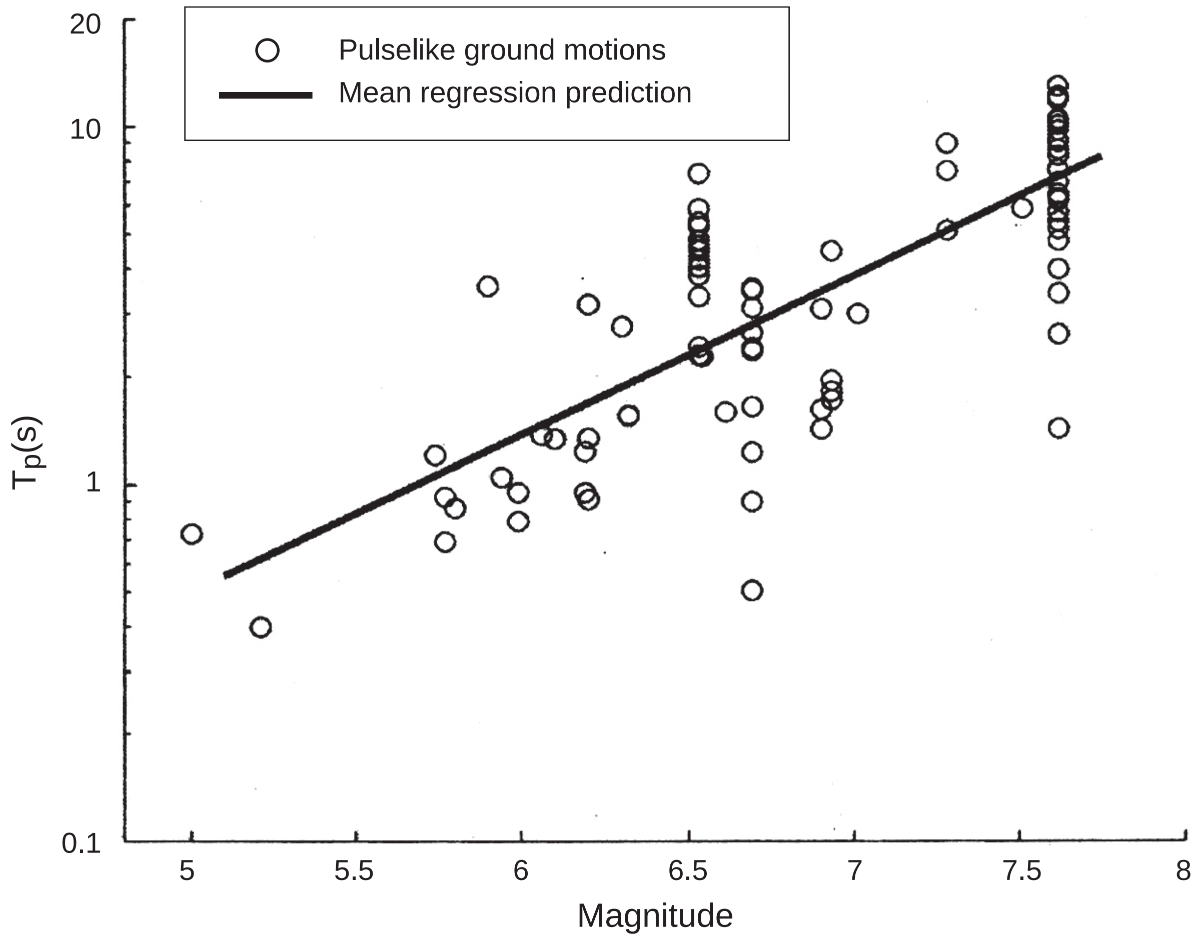

Figure 8
Correlation of pulse period with earthquake magnitude by Baker 2007

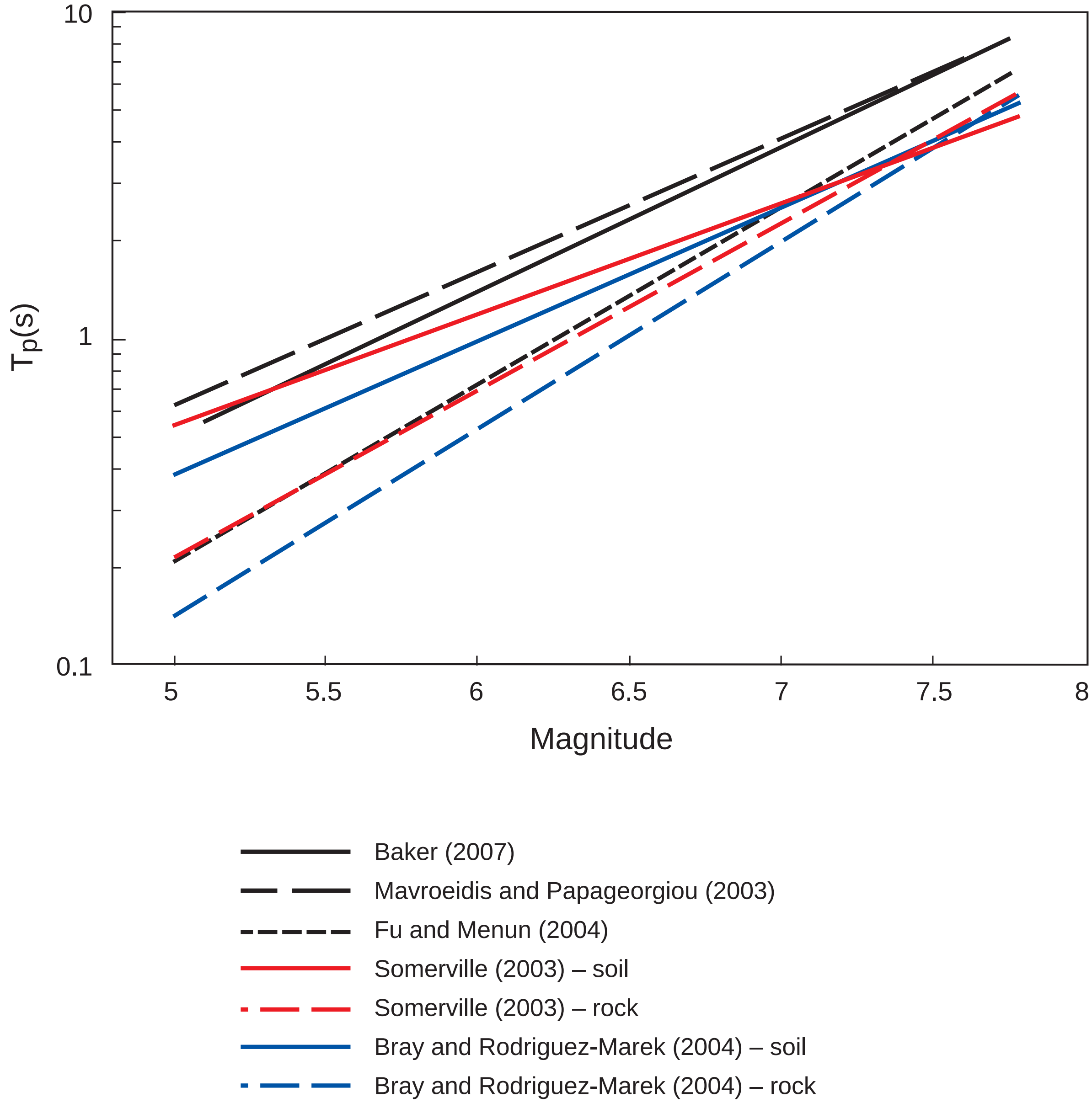

Figure 9
Correlations of pulse period with earthquake magnitude by different researchers