Design Ground Motion Library: An Interactive Tool for Selecting Earthquake Ground Motions

Gang Wang,[a] M.EERI, **Robert Youngs,**[b] M.EERI, **Maurice Power,**[b] M.EERI, **and Zhihua Li,**[b] M.EERI

The Design Ground Motion Library (DGML) is an interactive tool for selecting earthquake ground motion time histories based on contemporary knowledge and engineering practice. It was created from a ground motion database that consists of 3,182 records from shallow crustal earthquakes in active tectonic regions rotated to fault-normal and fault-parallel directions. The DGML enables users to construct design response spectra based on Next-Generation Attenuation (NGA) relationships, including conditional mean spectra, code spectra, and user-specified spectra. It has the broad capability of searching for time history record sets in the database on the basis of the similarity of a record's response spectral shape to a design response spectrum over a user-defined period range. Selection criteria considering other ground motion characteristics and user needs are also provided. The DGML has been adapted for online application by the Pacific Earthquake Engineering Research Center (PEER) and incorporated as a beta version on the PEER database website. [DOI: 10.1193/090612EQS283M]

INTRODUCTION

In performance-based seismic design of civil structures, it is critical to develop systematic methods and useful tools to search, select, and modify suitable ground motion time histories for engineering applications. In a project sponsored jointly by the California Geological Survey-Strong Motion Instrumentation Program (CGS-SMIP) and the Pacific Earthquake Engineering Research Center-Lifelines Program (PEER-LL), a multidisciplinary team of geotechnical engineers, seismologists, and structural engineers developed the Design Ground Motion Library (DGML; AMEC Geomatrix 2009).

Because only a limited number of ground motion records are available for rare design-level events, amplitude scaling of ground acceleration is commonly performed in earthquake engineering design practice. However, ground motion scaling has been a subject of intense debate over the years given that inappropriate record scaling can bias estimates of structural response (e.g., Luco and Bazzurro 2007). Significant concerns have been raised regarding the validity of the scaling process in several studies (e.g., Grigoriu 2011). On the other hand, it

[a] Hong Kong University of Science and Technology, Kowloon, Hong Kong
[b] AMEC Environment & Infrastructure, Inc., Oakland, CA

Earthquake Spectra, Volume 31, No. 2, pages 617–635, May 2015; © 2015, Earthquake Engineering Research Institute

has been reported that the degree of bias induced by record scaling systematically decreases as more constraints are applied on the process of ground motion selection and scaling (Hancock et al. 2008). In terms of geotechnical applications, Watson-Lamprey and Abrahamson (2006) demonstrated that, if ground motion selection and scaling are based on multiple well-selected parameters, ground motions can be scaled by large factors and still lead to unbiased estimates of earthquake-induced sliding displacements for slopes.

In terms of structural response, a number of studies have found that the elastic response spectrum over a period range of significance closely correlates with inelastic structural response (e.g., Shome et al. 1998, Baker and Cornell 2005, 2006). The period range of significance may include periods shorter than the fundamental structure period because of higher-mode effects and include periods longer than the fundamental structure period because of structure softening during inelastic response. Benchmark tests were recently conducted by the PEER Ground Motion Selection and Modification (GMSM) Working Group to quantify the accuracy of various GMSM schemes in predicting the median interstory drift response of buildings (Haselton 2009). The results demonstrated the importance of scaling records to account for the realistic spectral shape of ground motions at the design level. Especially, the conditional mean spectrum (CMS) describes the expected distribution of spectral accelerations at different periods for a scenario earthquake (Baker and Cornell 2006, Baker 2011). Ground motion records scaled to match the CMS have a realistic spectral shape at multiple periods, so they can better estimate the median interstory drift of buildings (Haselton 2009).

To explicitly account for the inelastic behavior of structures, ground motion–scaling methods are also developed using inelastic deformation spectra or the response of the first-mode inelastic single-DOF system (e.g., Luco and Cornell 2007, Kalkan and Chopra 2010, Reyes and Chopra 2012). In these procedures, important structure-specific properties, such as modal participation factors and structural strength, can be explicitly considered.

In summary, realistic estimates of inelastic response for different structure types require that ground motion selection and scaling be properly conducted by taking into account the structural characteristics and single or multiple ground motion parameters that significantly correlate with structural response. These considerations, as well as considerations of a range of preferences by designers and analysts (e.g., the size of the time history sets), indicated that a "dynamic" ground motion library was needed—that is, one that would permit the selection of time history records to be tailored to specific project needs and designer preferences. One of the objectives of developing the DGML was to create an efficient tool for time history selection that is consistent with contemporary knowledge and engineering practice. The DGML enables rapid searching and selection of time histories from a large ground motion database based on appropriate criteria and user needs. Moreover, it has the broad capability of searching for time history record sets in the database on the basis of (1) the characteristics of the recordings in terms of earthquake magnitude, type of faulting, distance, and site characteristics; (2) the response spectral shape of the records in comparison with 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. 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.

Initially developed on a DVD-ROM, the DGML has been adapted for online application by PEER and incorporated as a beta version on the PEER database web site (PEER 2012b). This paper summarizes the development of the DGML and its application in the selection and scaling of earthquake ground motions for seismic design of civil structures.

EARTHQUAKE GROUND MOTION DATABASE

DGML STRONG MOTION DATABASE

The source for the DGML is the PEER Next-Generation Attenuation (PEER-NGA) project database of ground motion recordings and supporting information (PEER 2012a), which was created as the principal resource for the development of updated ground motion prediction equations (GMPEs) in the NGA research project coordinated by the PEER Lifelines Program (PEER-LL) in partnership with the U.S. Geological Survey (USGS) and the Southern California Earthquake Center (SCEC) (Chiou et al. 2008, Power et al. 2008). The PEER-NGA database represents a comprehensive update and expansion of the preexisting PEER database. The ground motion records originate from the strong motion networks and databases of CGS-SMIP and USGS and other reliable international sources.

The PEER-NGA database includes 3,551 three-component recordings from 173 earthquakes and 1,456 recording stations. The DGML database consists of 3,182 records from the PEER-NGA database. Not incorporated were 369 records, including the following:

- Records considered to be from tectonic environments other than shallow crustal earthquakes in active tectonic regions, such as those from subduction zones.
- Records of earthquakes with poor-quality metadata.
- Records obtained in recording stations not considered sufficiently close to free-field ground surface conditions, such as those obtained in basements of buildings or on the ground floors of tall buildings.
- Records lacking information on soil/geologic conditions at recording stations.
- Records having only one horizontal component.
- Records not rotated to fault-normal (FN) and fault-parallel (FP) directions because of the absence of information on sensor orientations or fault strike.
- Records of questionable quality.
- Records that are proprietary.

Figure 1 shows the moment magnitude and rupture distance distribution of the records in the DGML database.

Acceleration time histories in the DGML are horizontal components that have been rotated to the FN and FP directions. However, this does not imply that these time histories are for use in analyses in the FN and FP directions only; rather, they can be used in time history sets in the same manner as are time histories in the as-recorded orientations in other databases. Nevertheless, FN and FP rotation does provide additional information with respect to the seismological conditions under which the recordings were obtained, and, as Somerville et al. (1997) found, records in the FN direction often contain strong velocity pulses that may be associated with rupture directivity effects.

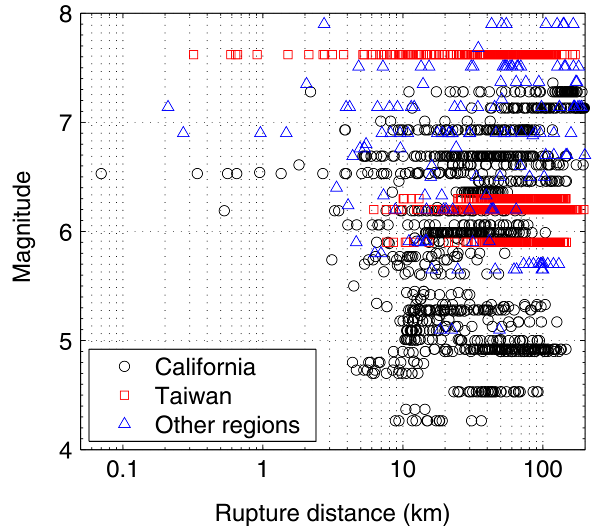

Figure 1. Moment magnitude and rupture distance distribution for PEER NGA records in the DGML database.

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. The recommended lowest usable frequency is related to the filtering of a record by the record-processing organization to remove low-frequency (long-period) noise. High-pass 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. The DGML user can choose to select or reject a record on the basis of 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. Metadata in the PEER-NGA database include the following:

- Earthquake source information, such as moment magnitude, type of faulting (mechanism), depth to the top of the fault rupture, and rupture directivity parameters.
- Source-to-recording station travel path information, such as different measures of source-to-site distance and recording station location on the hanging wall or foot-wall of the reverse or normal fault.
- Local site conditions at recording stations, such as average shear wave velocity in the upper 30 meters of sediments (V_{S30}) and depth to basement rock.

DGML metadata include earthquake magnitude and type of faulting, measures of closest distance from the earthquake source to the recording station (closest distance to the fault rupture surface and the Joyner-Boore distance), and site V_{S30}. The DGML also provides access to vertical ground motion time histories and their response spectra if available.

RECORDS WITH VELOCITY PULSES

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 as a result of near-source fault rupture directivity effects, can impose severe demands on structures (Bertero et al. 1978, Hall et al. 1995, Alavi and Krawinkler 2001, Makris and Black 2003, Mavroeidis et al. 2004, Akkar et al. 2005, Luco and Cornell 2007). The presence of velocity pulses can be a criterion in searches for DGML records.

In the PEER-NGA database, certain ground motion records have been identified as having strong velocity pulses that may be associated with fault rupture directivity effects. The following general criteria define such records (Baker 2007): (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 (the PGV of the pulse record should be equal to or greater than 30 cm/s). Although Somerville et al. (1997) showed that the strongest pulses are generally more closely aligned with the FN direction than with the FP direction, the criteria just listed apply to both FN and FP ground motion components in the NGA database. More detailed results and documentation of analyses can be found in Baker (2014). It is interesting that, even though velocity pulses may not seem apparent in some records in the FN or the FP direction, they may be present in other directions (Reyes and Kalkan 2012). However, the pulse records identified in the DGML are only for FN and FP components.

Besides the pulse records indentified by Baker (2007), several records having strong FN pulses are included in the DGML if they have been identified as pulse records in at least two studies by other researchers (Somerville 2003, Mavroeidis and Papageorgiou 2003, Bray and Rodriguez-Marek 2004, Fu and Menun 2004) and if their PGV is equal to or greater than 30 cm/s (Baker's criterion). In total, pulse records are identified in the DGML database as follows: 63 have pulses in FN components only; 23 have pulses in FP components only; and 30 have pulses in both FN and FP components. With the DGML user interface, records having FN pulses, FP pulses, or both FN and FP pulses can be searched. As with all DGML records, a user can specify other criteria and limits, as described in the next section.

There can be no assurance that the velocity pulses of DGML records are all due to directivity effects without detailed seismological study of individual records. It is likely that other seismological factors may have caused or contributed to some of them. However, although the causative mechanisms are uncertain, it is believed that the pulses are similar to those caused by directivity and are therefore suitable for use in modeling the effects of directivity pulses on structures. In addition to the commonly used ground motion parameters described previously, the DGML provides estimates of pulse periods, primarily based on Baker (2007). For a more detailed understanding 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.

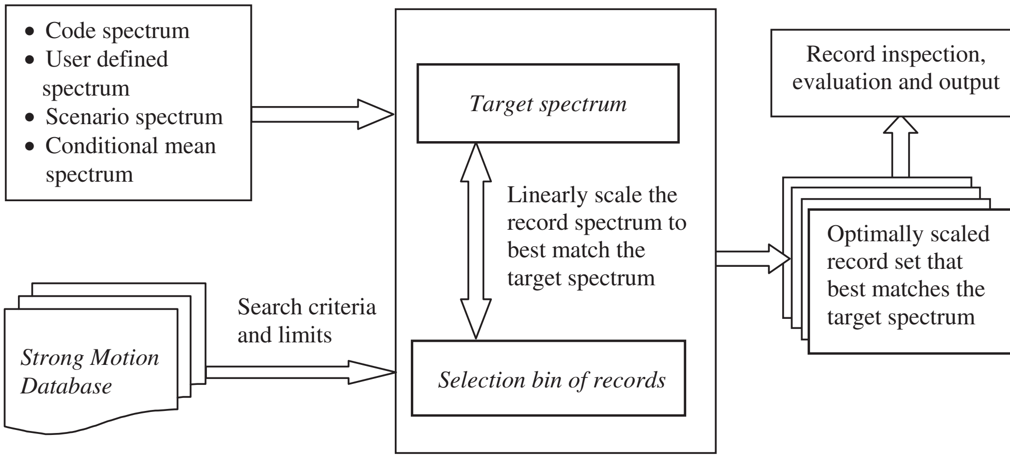

Figure 2. Flow chart of the DGML.

GROUND MOTION SELECTION CRITERIA AND PROCEDURES

The selection of ground motions by the DGML is based on response spectral shape and other criteria in a three-step process: (1) specification of the design or target response spectrum; (2) specification of criteria and limits for time history record searches; and (3) search of the database and selection and evaluation of records. A flow chart of the DGML is shown in Figure 2.

DEVELOPING THE TARGET SPECTRUM

The DGML Target Spectrum window is shown in Figure 3. It contains the following main parts: (1) Select Spectrum Model; (2) PEER-NGA Spectrum; (3) User Defined Spectrum; (4) Code Specification; (5) Control (plot control panel); (6) Spectrum plot; (7) Notations; (8) Save Target Spectrum button; and (9) Next button (to go to the next step in the search).

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

- Option 1: code spectrum. For this option, the target spectrum is the design earthquake or maximum considered earthquake (MCE) spectrum as formulated in the NEHRP provisions (Building Seismic Safety Council 2009, 2012), ASCE standards *ASCE 7-05* (ASCE 2006) and *ASCE 7*-10 (ASCE 2010), and the International Building Code (ICC 2006). The code design spectrum is completely specified by three parameters, which are obtained using design ground motion maps and other provisions in the code document: site-class-adjusted 0.2-s spectral acceleration, S_{DS}; site-class-adjusted 1.0-s spectral acceleration, S_{D1}; and 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 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; the tool then constructs and plots the spectrum. Such response spectra may be either probabilistic (uniform hazard spectrum, UHS) or deterministic (scenario earthquake) and developed by the user.
- Option 3: scenario spectrum based on PEER-NGA models. For this option, DGML constructs a deterministic scenario earthquake spectrum using a user-selected set of ground motion prediction models developed in the NGA project for shallow crustal earthquakes in active tectonic regions. Five ground motion prediction equations (GMPEs) were developed in the NGA project: Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), and Idriss (2008). The user enters earthquake, travel path, and site parameters (e.g., earthquake moment magnitude, type of faulting, fault-to-site distance, site V_{S30}, and other parameters needed for the selected NGA models), and the DGML constructs the individual response spectra and an average of them for the models.

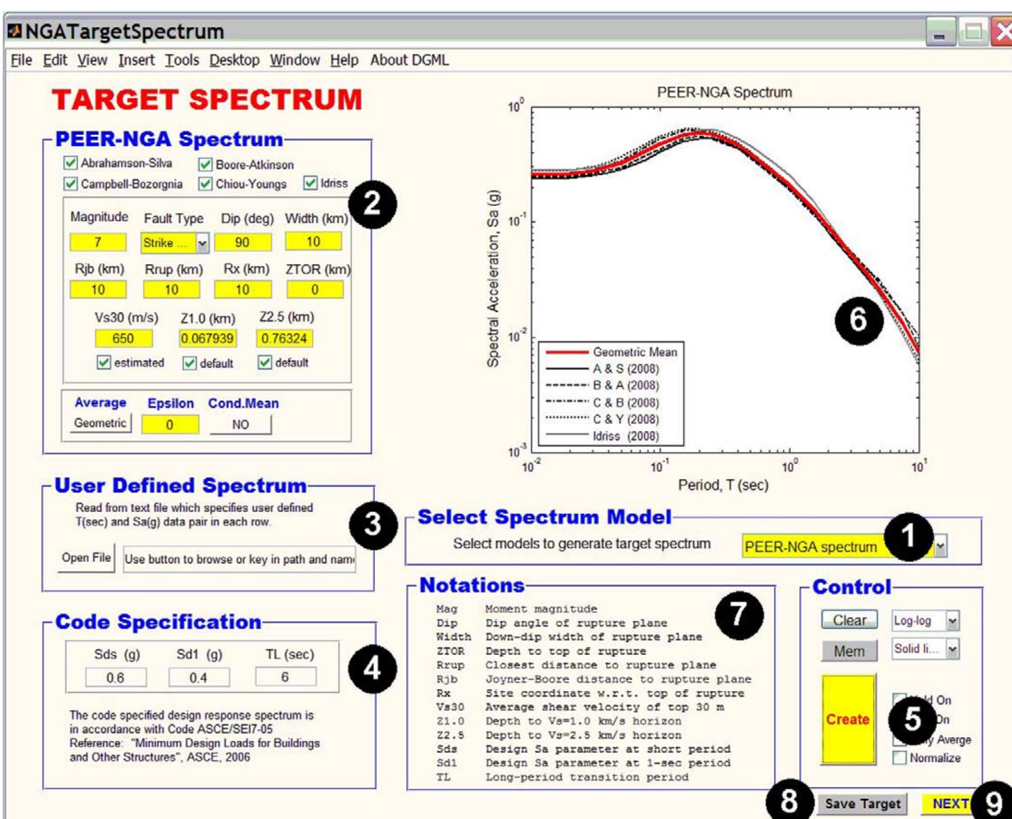

Figure 3. DGML Target Spectrum interface.

The DGML also has the capability to construct the conditional mean spectrum (CMS) for a scenario earthquake. Although in practice sets of time histories are often formed to provide an aggregate match to a probabilistic response spectrum (UHS), for design purposes there may be conservatisms involved in doing so. As summarized by Cornell (2006) and Baker (2011), the UHS is different from the response spectrum expected for a single ground motion from a scenario earthquake. The spectral ordinates of a UHS at different periods may be driven by two or more different scenario earthquake sources, and therefore the UHS may be overly broad and thus conservative for a single earthquake. On the other hand, conditional mean spectra can provide realistic spectral shapes for scenario earthquakes.

To construct conditional mean spectra, hazard deaggregation should be carried out first to identify the dominant deterministic earthquake scenarios that contribute to a UHS, including magnitudes (M) and rupture distances (R). The "epsilon," $\varepsilon(T_0)$, measures the number of standard deviations between the median spectrum of a scenario earthquake (based on M and R) and a given target spectral acceleration value at period T_0 as follows:

$$\varepsilon(T_0) = \frac{\ln Sa^{target}(T_0) - \overline{\ln Sa}(M, R, T_0)}{\sigma_{\ln Sa(T_0)}} \tag{1}$$

where $\ln Sa^{target}(T_0)$ is the specified target value of the logarithmic spectral acceleration at T_0, and $\overline{\ln Sa}(M, R, T_0)$ and $\sigma_{\ln Sa(T_0)}$ are the predicted mean and standard deviation, respectively, of the logarithmic spectral acceleration at period T_0 provided by the NGA models. The DGML allows the user to specify the $\varepsilon(T_0)$ value directly to construct the conditional mean spectrum from the following equation (Baker and Cornell 2006, Baker 2011):

$$\ln Sa^*(T) = \overline{\ln Sa}(M, R, T) + \rho(T, T_0) \times \sigma_{\ln Sa(T)} \times \varepsilon(T_0) \tag{2}$$

where $\ln Sa^*(T)$ is the conditional mean spectrum at period T, conditioned on a given target spectral acceleration value at period T_0, and $\rho(T, T_0)$ is the correlation coefficient between (logarithmic) spectral accelerations at T and T_0 (e.g., Baker and Jayaram 2008).

Figure 4a shows the construction of a conditional mean spectrum by the DGML. For this example, the median and median +1.5 standard deviation spectra are constructed using the NGA models based on a deterministic scenario ($M_w = 7$, $R_{rup} = 10$ km, strike-slip faulting, and rock site). The conditional mean spectra are conditional on the spectral acceleration at the level of 1.5 epsilon at the periods of 0.5 and 1 s, respectively, as specified by the DGML in this example. Multiple conditional mean spectra can be constructed for different conditioning periods. Figure 4b illustrates conceptually the construction of conditional mean response spectra for different periods for two scenario earthquakes to more closely match, in aggregate, a UHS design spectrum. As shown, for scenario earthquakes A and B a single conditional mean spectrum for each event could fall substantially below the UHS at periods distant from the period at which the conditional mean spectrum is at the target epsilon. Therefore, again as shown, two (or more) conditional mean spectra might be required for each scenario earthquake to satisfy code requirements for an aggregate match to the design UHS.

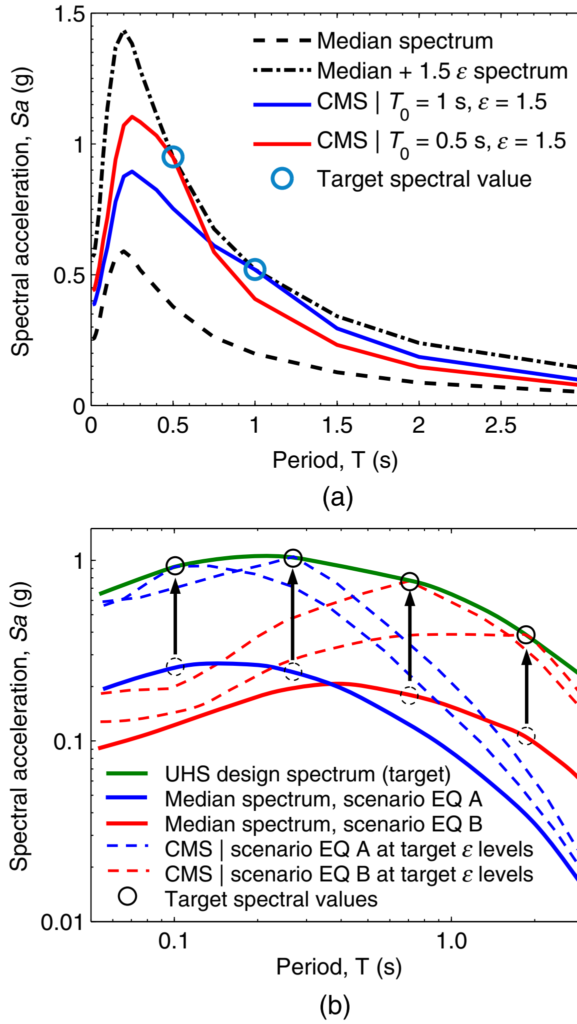

Figure 4. Construction of conditional mean spectrum by DGML: (a) conditioned on a scenario earthquake at periods of 0.5 s and 1 s at $\varepsilon = 1.5$ level; (b) conditioned on multiple scenario earthquakes based on Cornell (2006).

SPECIFYING CRITERIA AND LIMITS FOR SEARCHES

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 user-defined spectral 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 the user's general acceptance criteria and then ranks them in order of increasing MSE, with the best matches having the lowest MSE. It is worth pointing out that the target spectrum developed using the three options listed previously and the response spectrum of individual records in the database are both linearly interpolated in the log-log scale using a set of periods equally spaced from 0.01 to 10 s in log scale (100 points/log cycle; therefore, 301 periods from 0.01 to 10 s with end points included). The MSE is computed using the interpolated data via Equation 3:

$$\mathrm{MSE} = \frac{\sum_i w(T_i)\{\ln[Sa^{target}(T_i)] - \ln[f \times Sa^{record}(T_i)]\}^2}{\sum_i w(T_i)} \tag{3}$$

where f is a linear scale factor applied to the entire response spectrum of the recording and $w(T_i)$ 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 an equal weight to all periods (i.e., $w(T_i) = 1$), but the user may wish to emphasize the match over a narrow period range of interest while maintaining a reasonable match over a broad period range.

The DGML allows the user to select individual FN/FP component recordings that match the target spectrum; alternatively, the user can select recordings for which the geometric mean of the two horizontal FN/FP components matches the target spectrum. In the latter case, the MSE is computed over the two components using Equation 3 with the same value of f applied to both. This process maintains the relative amplitude of the two horizontal components.

Amplitude scaling of "as-recorded" strong ground motion acceleration time histories is used in the DGML, which does not alter the frequency content of the recordings. 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, which 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 3 is achieved by a scale factor given by the mean weighted residual in natural logarithm space between the target and the record spectra:

$$\ln f = \frac{\sum_i w(T_i) \ln[Sa^{target}(T_i)/Sa^{record}(T_i)]}{\sum_i w(T_i)} \tag{4}$$

The second option is to scale the records so that the spectral acceleration at a single period matches the target spectral acceleration at that period. This can be used to scale a set of records to have the same spectrum ordinate as the target conditional mean spectrum at the conditioning period, T_0. In this case, the scale factor is determined by

$$f = \frac{Sa^{target}(T_0)}{Sa^{record}(T_0)} \tag{5}$$

The third option is not to apply any scaling.

For all three scaling options, the MSE is computed using Equation 3. Also, all options require 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 the target spectrum and the spectra of recordings over the user-specified period range of significance. In the DGML, the weight function is also discretized at each T_i. It represents only relative weights assigned to various discrete periods and is normalized in the program such that its summation over discrete period points equals unity. For this reason, the absolute value of the weight function is immaterial.

The user specifies the ranges of parameters over which searches are to be conducted and other limits and restrictions. 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 components (i.e., arbitrary FN or FP components, no restriction; FN components only; FP components only; FN and FP components in pair).

Other criteria to be specified by the user are total number of records to be displayed and total number of records for which the average spectrum will be calculated. Figure 5 shows the DGML Search Engine graphical interface used to specify the primary search criteria and list

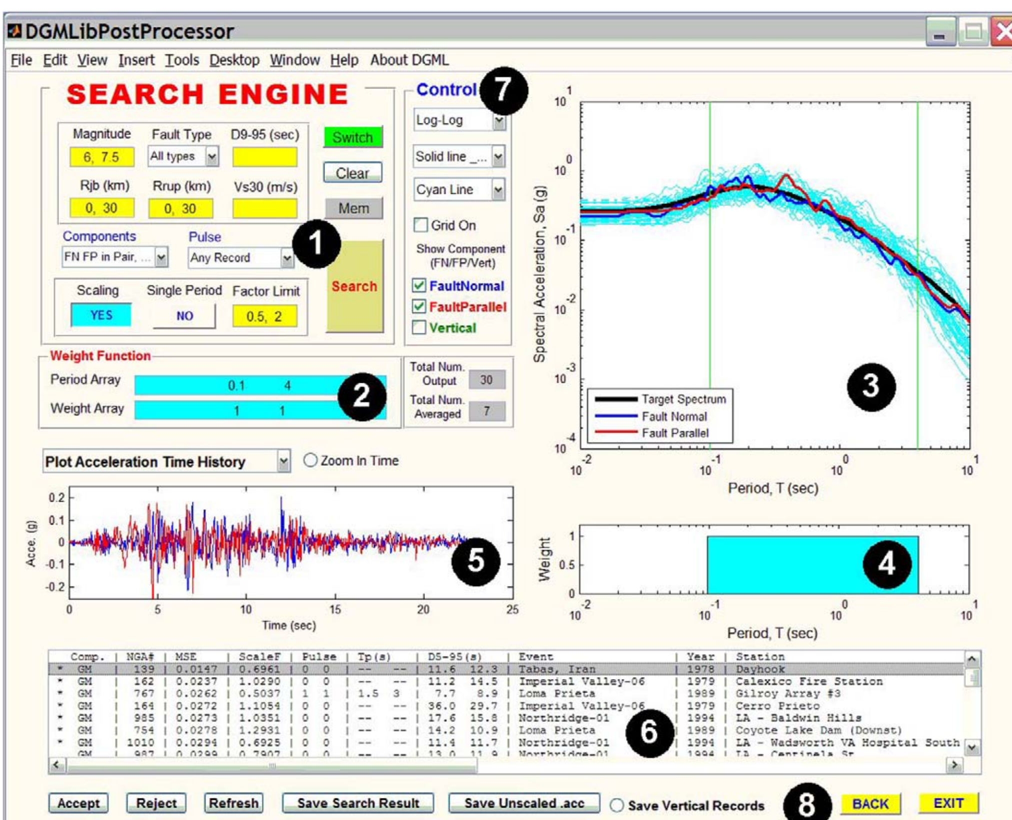

Figure 5. DGML Search Engine interface.

and plot results, including time histories and individual and average response spectra of scaled records sets compared with a specified design or target spectrum. The eight main function modules are (1) Search Engine (specifies record acceptance criteria and performs the search); (2) Weight Function (specifies the weight function to be used for scaling records); (3) spectra-plotting window; (4) weight function–plotting window; (5) Plot Acceleration (or Velocity/Displacement) Time History for a selected record (one-, two-, or three-component time histories of a record can also be viewed at an expanded time scale to examine details, using a feature called Zoom in Time); (6) ground motion record information output list; (7) graphic control panel for line styles and display of ground motion components; and (8) buttons to accept or reject individual records and to save the results and selected acceleration time history files. Figure 6 shows individual spectra and the average spectrum of selected records compared with the target spectrum. Figure 7 shows the spectra of three components of an individual record (FN, FP, and vertical) and its acceleration, velocity, and displacement time histories.

SELECTION AND EVALUATION OF GROUND MOTION RECORDS

The software tool scans the database, selects all records meeting the user-specified criteria as summarized previously, scales the chosen records to match the target spectrum, and ranks them in order of increasing MSE. The DGML also has a supplementary search function to search for specific records according to specified NGA record sequence numbers or earthquake or recording station name. Selected records from a supplementary search are scaled and ranked by MSE and can be incorporated into 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 their preferences.

For a selected record set, a search report can be automatically generated and exported. It includes the following:

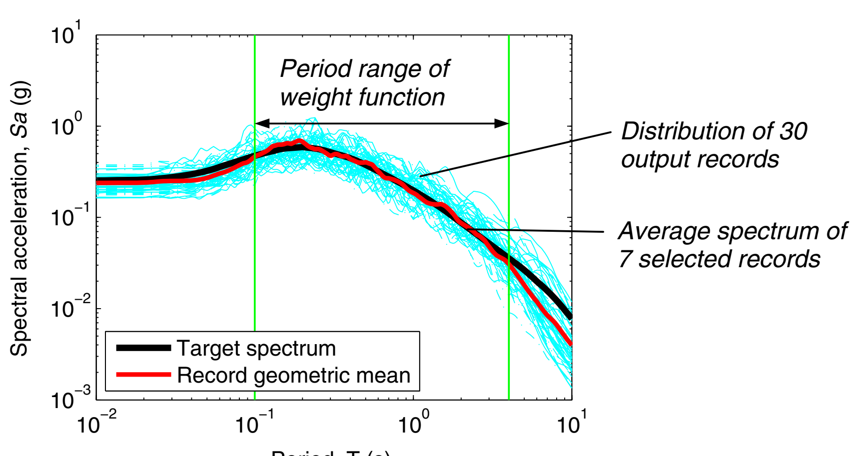

Figure 6. Example of an average spectrum of selected records.

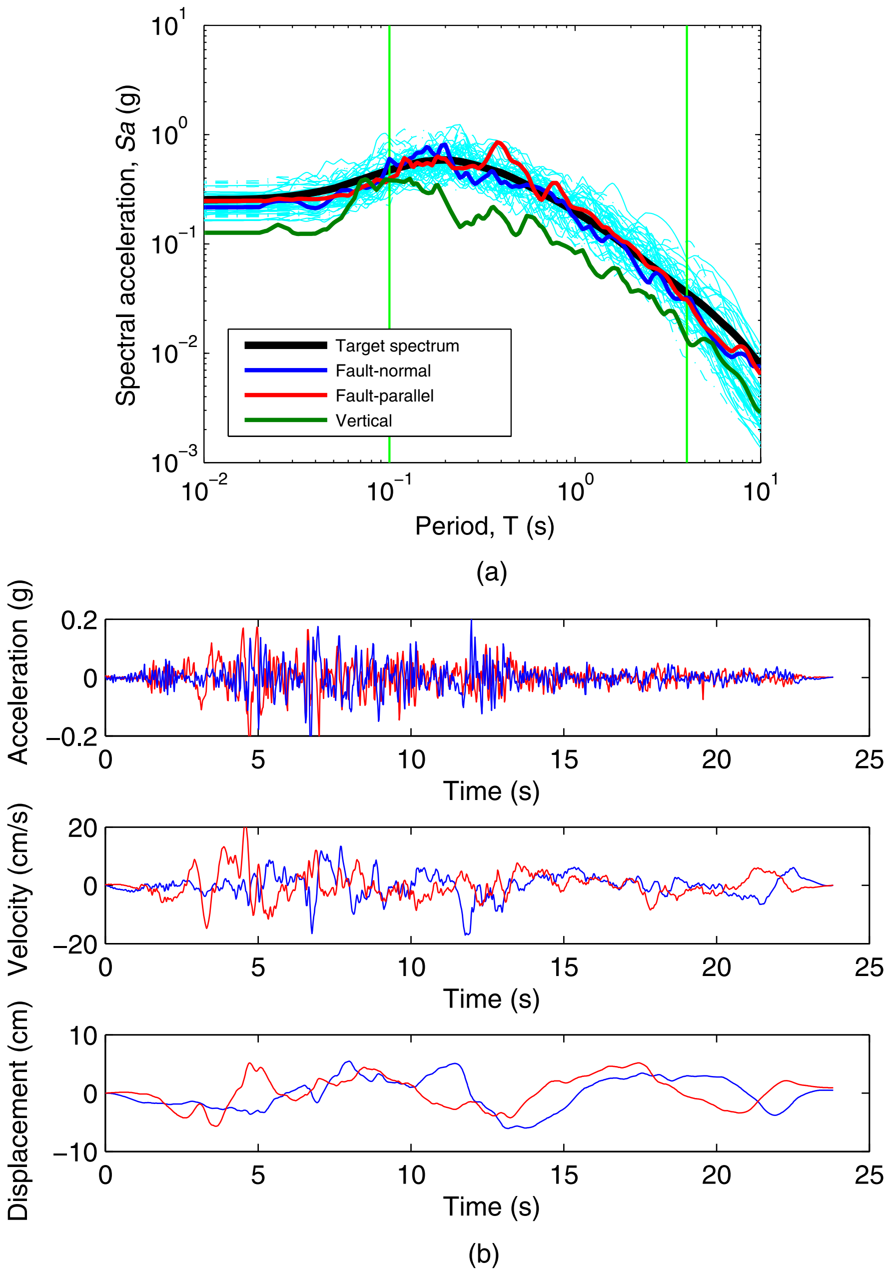

Figure 7. Highlight of the response spectrum and time history of an individual record: (a) FN, FP, and vertical response spectrum; (b) FN and FP acceleration, velocity, and displacement time histories.

- Summaries of the search criteria and earthquake, distance, and station/site information.
- Record-scaling factors and MSEs.
- Scaled record characteristics, including PGA, PGV, PGD, response spectral accelerations, presence of pulses and pulse periods, significant durations, and recommended lowest usable frequencies.
- Scaled average spectral accelerations for the selected record set along with the target or design spectral accelerations.

Although the search results are based on horizontal records, the response spectra for the corresponding vertical records, scaled by the same factors as for the horizontal records, can be saved in the search report, which can be output in an Excel spreadsheet. Spectra and time history plots can be saved as figure files. The horizontal and/or vertical components of the selected acceleration time histories can be saved as well; these are the unscaled original data from the PEER-NGA database.

The user can further modify the time histories for other purposes (e.g., fine-tune record-scaling factors to meet building code requirements, rotate time histories, or adjust the match of record spectra to a design spectrum by altering the frequency content). For example, *ASCE 7-05* and *ASCE 7-10* specify that for two-dimensional analysis the average value of the 5%-damped response spectra for the set of time histories used shall be not less than the design response spectrum for periods ranging from $0.2T_1$ to $1.5T_1$, where T_1 is the natural period of the structure in the fundamental mode for the direction of the response being analyzed (ASCE 2006, 2010). This criterion can be easily checked using the average of the spectra for the scaled time histories provided by the DGML search report and then applying a minor adjustment factor to the set of records to meet the criterion.

For three-dimensional analysis of structures, *ASCE 7-10* specifies that, in the period range T_i from $0.2T_1$ to $1.5T_1$, the average of the square root of the sum of squares (SRSS) spectra ($\sqrt{Sa_{FN}^2(T_i) + Sa_{FP}^2(T_i)}$) from all time history pairs shall not fall below the corresponding ordinate of the response spectrum used in the design. Again, with a little effort the criterion can be checked using the DGML output in Excel format. The user first computes the SRSS spectrum for each pair of time histories and then compares the average of the SRSS spectra with the design spectrum, as shown in Figure 8. The DGML scales the selected time histories by comparing the geometric mean for each pair of records to the target spectrum. The average of the geometric mean spectra selected by the DGML provides a good match to the target design spectrum. The corresponding average of the SRSS spectra has a shape similar to that of the average of the geometric mean spectra but is higher, as expected. Comparison of the average SRSS spectrum with the design spectrum in the period range of interest provides a scale factor (0.76 in this case) that can be applied to the suite of selected records to meet the criterion.

For the special case of three-dimensional analysis of sites located within 3 mi (5 km) of the active fault that controls the hazard, *ASCE 7-10* requires that each pair of components be rotated to the fault-normal and fault-parallel directions of the causative fault and scaled so that the average of the FN components is not less than the risk-targeted MCE (MCE_R) response spectrum. The DGML facilitates meeting this criterion by first defining a target spectrum as the MCE_R spectrum and searching for FN components only, and then adjusting

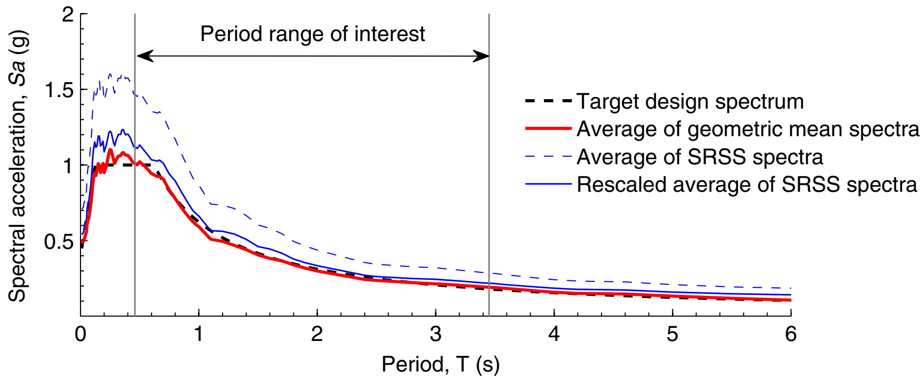

Figure 8. Adjustment of the selected ground motion records to the *ASCE 7-10* code design spectrum for three-dimensional analysis.

the scaling of the FN components to meet the criterion in the same way as for the two-dimensional analysis case. The pairing of FP components is scaled by the same factors.

SUMMARY AND DISCUSSION

The successful development of the DGML is the outcome of a multidisciplinary team effort. The DGML is a state-of-the-art software package that enables interactive selection and modification of time histories for dynamic analysis of structures based on appropriate selection criteria and user needs. It facilitates the construction of design response spectra using recently developed NGA relationships, including conditional mean spectra, and the construction of code and any other user-specified spectra. The DGML has the broad capability of searching for time history record sets in the library database on the basis of response spectral shape, characteristics of the recordings in terms of earthquake magnitude and type of faulting, distance, site characteristics, duration, and presence of velocity pulses in near-fault time histories.

The DGML features a Graphic User Interface (GUI) to facilitate data input, visualization, and processing. Results in each step can be visualized, and those for different sets of input parameters can be easily compared. Users can inspect the response spectra and acceleration/velocity/displacement time histories for each record for each component. The DGML also provides easy ways to output search results, plots, and tables. Files containing acceleration time histories of selected records can be saved for each project. The DGML algorithm is robust and efficient. The search engine can scan and sort the database within a few seconds.

It is worth pointing out that the ground motions selected by the DGML mainly aim at estimating the median response of structures based on an elastic target spectrum. Sometimes it is important to obtain the actual dispersion of structural behaviors in performance-based earthquake design. For this purpose, ground motion selection algorithms for matching the target response spectrum mean and variance were recently developed (Wang 2011, Jayaram et al. 2011). These new developments will be readily implementable in the DGML in the future.

The DGML prototype was developed using the Matlab (version 7.2) GUI, and it can be executed or modified in the Matlab environment. The DGML's Matlab codes have been compiled into a stand-alone executable using the Matlab Compiler, so the Matlab environment is not required for end users. In 2009, the compiled DGML package (version 2) was released in DVD-ROM format and distributed to a small group of experts for testing, evaluation, and review. It has since been adapted for online application by PEER and incorporated as a beta version on the PEER database website (PEER 2012b). The online application enables broad access to the ground motion selection tool.

The DGML is currently limited to recorded time histories from shallow crustal earthquakes in active tectonic regimes. With the completion of the PEER NGA-West2 program, a greatly expanded ground motion database (Ancheta et al. 2013) and updated attenuation relationships have been developed and can be incorporated in a future update of the DGML. Time histories from subduction zone earthquakes are not as yet part of the DGML, but future developments will have the capability to add records from subduction zone earthquakes occurring in coastal regions of northwestern California, Oregon, Washington, and Alaska; they may also supplement the library of recorded time histories with time histories simulated by ground motion modeling. The DGML can be easily upgraded to accommodate these future developments.

ACKNOWLEDGMENTS

The DGML was jointly sponsored by the California Geological Survey Strong Motion Instrumentation Program (CGS-SMIP) and the Pacific Earthquake Engineering Research Center Lifelines Program (PEER-LL). In addition to the authors, project team members include Faiz Makdisi, Chih-Cheng Chin, Allin Cornell, Jack Baker, Stephen Mahin, Ronald Hamburger, Ronald Mayes, Roupen Donikian, Yusof Ghanaat, Walter Silva, Paul Somerville, and Ignatius Po Lam. We thank representatives of the project sponsors for their active participation, including Moh-Jiann Huang, Anthony Shakal, Yousef Bozorgnia, Brian Chiou, Thomas Shantz, and Norman Abrahamson. We also thank Tony Yang for his help with compiling the DGML software package. Gang Wang is supported by the Hong Kong Research Grants Council (RGC) grant 620311 and Direct Allocation Grants DAG12EG07-3 and FSGRF13EG09 (HKUST/RGC). Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the view of the sponsors and other individuals.

REFERENCES

Abrahamson, N. A., and Silva, W. J., 2008. Summary of the Abrahamson & Silva NGA ground-motion relations, *Earthquake Spectra* **24**, 67–97.

Akkar, S., Yazgan, U., and Gulkan, P., 2005. Drift estimates in frame buildings subjected to near-fault ground motions, *Journal of Structural Engineering* **131**, 1014–1024.

Alavi, B., and Krawinkler, H., 2001. *Effects of Near-Fault Ground Motions on Frame Structures, Blume Center Report #138*, Stanford University, Stanford, CA.

AMEC Geomatrix, 2009. *Design Ground Motion Library*, Report and Software Package, Oakland, CA.

American Society of Civil Engineers (ASCE), 2006. *Minimum Design Loads for Buildings and Other Structures, ASCE 7-05*, Reston, Virginia.

American Society of Civil Engineers (ASCE), 2010. *Minimum Design Loads for Buildings and Other Structures, ASCE 7-10*, Reston, Virginia.

Ancheta, T. D., Darragh, R. B., Stewar, J. P., Seyhan, E., Silva, W. J., Chiou, B. S.-J., Wooddell, K. E., Graves, R. W., Kottke, A. R., Boore, D. M., Kishida, T., and Donahue, J. L., 2013. *PEER NGA-West2 Database, PEER Report 2013/03*, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

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

Baker, J. W., 2011. Conditional mean spectrum: Tool for ground motion selection, *Journal of Structural Engineering* **137**, 322–331.

Baker, J. W., 2014. Website of the Baker Research Group, available at http://web.stanford.edu/~bakerjw/pulse-classification.html (last accessed 30 January 2015).

Baker, J. W., and Cornell, C. A., 2005. A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon, *Earthquake Engineering and Structural Dynamics* **34**, 1193–1217.

Baker, J. W., and Cornell, C. A., 2006. Spectral shape, epsilon and record selection, *Earthquake Engineering and Structural Dynamics* **35**, 1077–1095.

Baker, J. W., and Jayaram, N., 2008. Correlation of spectral acceleration values from NGA ground motion models, *Earthquake Spectra* **24**, 299–317.

Bertero, V., Mahin, S., and Herrera, R., 1978. Aseismic design implications of near-fault San Fernando earthquake records, *Earthquake Engineering and Structural Dynamics* **6**, 31–42.

Boore, D. M., and Atkinson, G. M., 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5% damped PSA at spectral periods between 0.01s and 10.0s, *Earthquake Spectra* **24**, 99–138.

Bray, J. D., and Rodriguez-Marek, A., 2004. Characterization of forward-directivity ground motions in the near-fault region, *Soil Dynamics and Earthquake Engineering* **24**, 815–828.

Building Seismic Safety Council of the National Institute of Building Sciences, 2009. *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, FEMA Report P-750*, Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council of the National Institute of Building Sciences, 2012. *NEHERP Recommended Seismic Provisions: Design Examples, FEMA Report P-751*, Federal Emergency Management Agency, Washington, D.C.

Campbell, K. W., and Bozorgnia, Y., 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5% damped linear elastic response spectra for periods ranging from 0.01s to 10.0s, *Earthquake Spectra* **24**, 139–171.

Chiou, B., Darragh, R., Gregor, N., and Silva, W., 2008. NGA project strong-motion database, *Earthquake Spectra* **24**, 23–44.

Chiou, B. S. J., and Youngs, R. R., 2008. Chiou-Youngs NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters, *Earthquake Spectra* **24**, 173–215.

Cornell, C. A., 2006. Should uniform hazard spectra be used for design? How should design response spectra be determined considering uniform hazard spectra from design maps and hazard deaggregation data? *presentation to the Third ATC-35/USGS National Earthquake Ground Motion Mapping Workshop*, 7–8 December 2006, San Mateo, CA.

Fu, Q., and Menun, C., 2004. Seismic-environment-based simulation of near-fault ground motions, in *Proceedings, 13th World Conference on Earthquake Engineering*, Paper No. 332, 1–6 August 2004, Vancouver, Canada.

Grigoriu, M., 2011. To scale or not to scale seismic ground-acceleration records, *Journal of Engineering Mechanics* **137**, 284–293.

Hall, J. F., Heaton, T. H., Halling, M. W., and Wald, D. J., 1995. Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra* **11**, 569–605.

Hancock, J., Bommer, J. J., and Stafford, P. J., 2008. Numbers of scaled and matched accelerograms required for inelastic dynamic analyses, *Earthquake Engineering and Structural Dynamics* **37**, 1585–1607.

Haselton, C. B. (ed.), 2009. *Evaluation of Ground Motion Selection and Modification Methods: Predicting Median Interstory Drift Response of Buildings, PEER Report 2009/01*, Ground Motion Selection and Modification Working Group, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Idriss, I. M., 2008. An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes, *Earthquake Spectra* **24**, 217–242.

International Code Council (ICC), 2006. *International Building Code*, Washington, D.C.

Jayaram, N., Lin, T., and Baker, J. W., 2011. A computationally efficient ground-motion selection algorithm for matching a target response spectrum mean and variance, *Earthquake Spectra* **27**, 797–815.

Kalkan, E., and Chopra, A. K., 2011. Modal-pushover-based ground-motion scaling procedure, *Journal of Structural Engineering* **137**, 298–310.

Luco, N., and Bazzurro, P., 2007. Does amplitude scaling of ground motion records result in biased nonlinear structural drift responses? *Earthquake Engineering and Structural Dynamics* **36**, 1813–1835.

Luco, N., and Cornell, C. A., 2007. Structure-specific scalar intensity measures for near-source and ordinary earthquake ground motions, *Earthquake Spectra* **23**, 357–392.

Makris, N., and Black, C., 2003. *Dimensional analysis of inelastic structures subjected to near fault ground motions, EERC 2003-05*, Earthquake Engineering Research Center, Berkeley, California.

Mavroeidis, G. P., Dong, G., and Papageorgiou, A. S., 2004. Near-fault ground motions, and the response of elastic and inelastic single-degree-of-freedom (SDOF) systems, *Earthquake Engineering and Structural Dynamics* **33**, 1023–1049.

Mavroeidis, G. P., and Papageorgiou, A. S., 2003. A mathematical representation of near-fault ground motions, *Bulletin of the Seismological Society of America* **93**, 1099–1131.

Pacific Earthquake Engineering Research Center (PEER), 2012a. NGA Database, available at http://peer.berkeley.edu/nga/ (last accessed 30 January 2015).

Pacific Earthquake Engineering Research Center (PEER), 2012b. Strong Ground Motion Database, available at http://peer.berkeley.edu/products/strong_ground_motion_db.html (last accessed 30 January 2015).

Power, M., Chiou, B., Abrahamson, N., Bozorgnia, Y., Schantz, T., and Roblee, C., 2008. An overview of the NGA project, *Earthquake Spectra* **24**, 3–21.

Reyes, J. C., and Chopra, A. K., 2012. Modal pushover-based scaling of two components of ground motion records for nonlinear RHA of structures, *Earthquake Spectra* **28**, 1243–1267.

Reyes, J. C., and Kalkan, E., 2012. *Should Ground-motion Records Be Rotated to Fault-Normal/Parallel or Maximum Direction for Response History Analysis of Buildings? Open-File Report 2012–1261*, USGS, Menlo Park, CA.

Shome, N., Cornell, C. A., Bazzurro, P., and Carballo, J. E., 1998. Earthquake records and nonlinear response, *Earthquake Spectra* **14**, 469–500.

Somerville, P. G., 2003. Magnitude scaling of the near fault rupture directivity pulse, *Physics of the Earth and Planetary Interiors* **137**, 12.

Somerville, P. G., Smith, N. F., Graves, R. W., and Abrahamson, N. A., 1997. Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity, *Seismological Research Letters* **68**, 199–222.

Wang, G., 2011. A ground motion selection and modification method capturing response spectrum characteristics and variability of scenario earthquakes, *Soil Dynamics and Earthquake Engineering* **31**, 611–625.

Watson-Lamprey, J., and Abrahamson, N., 2006. Selection of ground motion time series and limits on scaling, *Soil Dynamics and Earthquake Engineering* **26**, 477–482.

(Received 6 September 2012; accepted 3 October 2013)