DESIGN GROUND MOTION LIBRARY: A PROGRESS REPORT

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Abstract

A Design Ground Motion Library (DGML) is being developed that will contain selected recorded acceleration time histories considered to be suitable for use by engineering practitioners for the time history dynamic analysis of various facility types in California and other parts of the Western United States. The DGML will include: (1) the electronic library of selected time histories and their associated ground motion parameters and supporting information on the earthquake source, travel path, and site characteristics; and (2) detailed guidelines for forming and scaling sets of time histories for applications. The characteristics of the seismic environment, including earthquake magnitude, faulting mechanism, source-to-site distance, near-fault directivity conditions, and site conditions, and the damaging characteristics of time histories are being incorporated into criteria for selecting and binning records for the library.

Introduction

This paper presents a progress report on the development of a Design Ground Motion Library (DGML) of recorded acceleration time histories of ground motion suitable for use by engineering practitioners for time-history analysis of various facility types in California and other parts of the western United States. The DGML project is jointly sponsored by the California Strong Motion Instrumentation Program (CSMIP) and the Pacific Earthquake Engineering Research Center (PEER)-Lifelines Program. The project was initiated in August 2002 and extends through December 2003.

Currently, there are a number of data bases of ground motion time histories recorded during earthquakes, e.g. PEER, COSMOS, CSMIP, and USGS. These data bases contain large numbers of ground motion records but do not provide guidance to the engineering practitioner as to how to select sets of records for time history analyses for specific facilities. In contrast to a data base, the DGML will comprise a smaller collection of records considered to be especially suitable for applications along with guidelines for assembling and scaling sets of records for these applications. The DGML is currently limited to recorded time histories from shallow crustal earthquakes of the types that occur in the western United States. Time histories recorded during subduction zone earthquakes will not be part of the library during this project. However, the project sponsors envision that future development of the DGML will add records from subduction zone earthquakes (appropriate for these types of earthquakes occurring in northwest California, Oregon, Washington, and Alaska) and will also supplement recorded motions with time histories simulated by seismological ground motion modeling methods.

The principal strategy in conducting the project is to utilize a team that is expert in selection and use of time history records to develop the criteria for the DGML, select the records for the DGML using the criteria and judgment, and develop guidelines for utilizing the DGML for applications. Accordingly, a multi-disciplinary project team of practitioners and researchers in structural engineering, geotechnical engineering, and seismology is conducting the project. The team comprises expertise in the time history dynamic analysis of building, 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 (Maurice Power, Robert Youngs, and Faiz Makdisi); Simpson Gumpertz & Heger, Inc. (Ronald Hamburger and Ronald Mayes); T.-Y. Lin International (Roupen Donikian); Quest Structures (Yusof Ghanaat); Pacific Engineering & Analysis (Walter Silva); URS Corporation (Paul Somerville); Earth Mechanics (Ignatius Po Lam); Professor Allin Cornell, Stanford University; and Professor Stephen Mahin, University of California, Berkeley.

Specific Project Objectives and Tasks

The specific objectives of the DGML project are:

(1) To develop an electronic Design Ground Motion Library containing the selected ground motion time histories.

(2) To develop utilization guidelines for forming and scaling time history record sets for applications.

(3) To identify the limits of applicability and deficiencies of the DGML and provide recommendations for further development.

The primary tasks being undertaken to achieve the objectives are:

Task 1 - Review of previous relevant efforts and information.

Task 2 - Development of criteria for the DGML.

Task 3 - Selection, analysis, and placement of records in the DGML based on the developed criteria and judgment.

Task 4 - Development of utilization guidelines for the DGML

Task 5 - Testing, evaluation, and finalization of the DGML

Task 6 - Preparation of final report including recommendations for further development.

Task 1 includes: review of existing ground motion libraries and databases; review of current knowledge of time history characteristics important to structure response and performance; and review of current practice and existing guidelines for selecting and scaling time history records. These reviews have been conducted and are continuing, especially with regard to ongoing research on the relation of time history characteristics and structure performance.

The principal tasks are 2, 3, and 4. Criteria development for the DGML, Task 2, is in progress, and the selection of records in Task 3 will utilize the results of that task. Preliminary work has been done on utilization guidelines, Task 4. Tasks 2 and 4 are discussed in sections below. Task 5 provides for the project team and selected other users to conduct trial usage of the DGML so that modifications can be made to the electronic package and the utilization guidelines during the DGML finalization process.

Criteria Development

Elements of criteria for the DGML are: time history record characteristics to be quantified; supporting information on records to be included; structure of the DGML; and criteria for including or excluding records in the DGML.

Record Characteristics

It is desirable, but not necessarily essential, that characteristics or parameters of records selected to be quantified for records in the DGML satisfy two criteria: First, the parameters should be known to correlate with structural or ground performance, thus permitting records to be selected with knowledge of their relative damageability. Second, the parameters should be definable as a function of the seismic environment such as magnitude, distance, type of faulting, and subsurface site conditions; that is, attenuation relationships for the parameters should be available.

One of the focus areas for PEER's performance-based engineering methodology development is the evaluation of the correlation of ground motion parameters with their damageability or inelastic structural response. This work is ongoing. Some of the parameters that have been considered by PEER, CSMIP, and other organizations as indicators of damage potential are listed in Table 1.

Table 1
Record Parameters (Intensity Measures)
to be Considered for Quantification in DGML

• PGA, PGV, PGD • Elastic response spectra • Inelastic response spectra • Duration • Cumulative Absolute Velocity (CAV) • Energy	• Damage indices • Arias Intensity • Housner Spectrum Intensity • Near-source characteristics - pulse velocity - pulse period - no. of pulses

Parameters that have been traditionally correlated with deformations and failure of the ground (soil liquefaction, slope stability and deformations) are peak ground acceleration (PGA) and duration of shaking (the latter typically quantified as the time to build up a fraction of the Arias Intensity, I_a, of a time history, say the time to buildup from 5% to 95% or from 5% to 75% of I_a). Kramer and Mitchell (2003), in studies for PEER, proposed the use of cumulative absolute velocity (CAV) as a parameter correlated with the development of excess pore water pressure and liquefaction in soils. Travasarou et al. (2003), also in studies for PEER, proposed the use of Arias Intensity as a parameter correlated with damage to stiff systems such as short-period structures and stiff soil slopes. Both CAV and I_a contain the effects of ground motion duration as well as amplitude because the parameters are summed over the duration of the time history.

A number of studies by PEER and PEER-Lifelines Program have indicated the strong correlation between structure damageability and elastic response spectral characteristics, either at the fundamental period of a structure or at a discrete number of periods or over a period range in order to capture ground motion intensity for higher modes of vibration (shorter periods), or at longer periods reflecting structural softening as damage occurs (e.g., Shome et al., 1998; Cordova et al., 2001; Luco and Cornell, 2003; Bazzurro and Luco, 2003; Cornell, 2003; Jalayer, 2003).

Inelastic response spectra have been found to improve the prediction of inelastic response and damage in some studies by PEER and PEER-Lifelines Program (e.g. Luco and Cornell, 2003; Bazzurro and Luco, 2003). Damage indices or damage spectra combining different measures of inelastic response (e.g. ductility and hysteretic energy) may also improve predictions of damageability (e.g. Bozorgnia and Bertero, 2002, in studies for CSMIP).

Near-source time history record characteristics, i.e. the strong pulsive ground motion characteristics associated with fault rupture directivity toward a site especially for the fault-strike-normal component of motion (e.g. pulse velocity, pulse period, and number of pulses) have been shown to be very damaging in studies by Krawinkler and Alavi (1998) for CSMIP. In-progress studies by Bazzurro and Luco (2003) for PEER-Lifelines Program have not shown a significant improvement in damage predictability associated with pulse period or velocity over the correlation with elastic response spectral characteristics alone for a data set of spectrum-matched near-source time histories.

The preceding are only a few examples of studies of time history characteristics related to structure damageability. To date, except for strong evidence that the elastic response spectrum and response spectral shape are strongly correlated with inelastic structural response (by virtue of their capturing the intensity of ground motions at structural periods of significance), there does not seem to be a strong consensus on the degree to which other parameters improve damage predictions. The importance of other parameters may be very structure-dependent. Knowledge in this area may be expected to increase rapidly.

With regard to ground motion attenuation relationships available to date to predict the parameters in Table 1 as a function of the seismic environment and site conditions, such relationships are available only for PGA, PGV, elastic response spectra, duration, Arias Intensity, and to a more limited degree, for near-source ground motion pulse characteristics.

Knowledge of the relationships of the parameters in Table 1 with damage and development of attenuation relationships for these parameters will increase with time. Therefore, the approach in the DGML project will be to quantify for time histories in the DMGL all of the parameters in Table 1 that are considered by the project team as potentially useful in damage estimation for some structure types or in ground failure estimation. Some of the parameters have multiple definitions or formulations (e.g. inelastic response spectra, energy, damage indices), and the specific definitions will need to be selected.

Supporting Information

Table 2 summarizes the types of supporting information that will be included for the records in the DGML. This information pertains to the parameters of the causative earthquake, source-to-site travel path, and site conditions at the ground motion recording station. Currently, supporting information for records in the PEER strong motion data base is being updated and added to as part of a project sponsored by PEER-Lifelines Program, USGS, and SCEC to develop next-generation attenuation relationships for western U.S. shallow crustal earthquakes (NGA project). The updated and additional information, to be available this summer, will be included for records placed in the DGML.

Table 2
Supporting Information about Records to be Quantified in DGML

• Earthquake magnitude	• Near-fault directivity parameters
• Faulting mechanism	• Site classification(s)
• Hanging wall vs. foot wall	• Basin response influence
• Source-to-site distance	

The near-fault directivity parameters referred to in Table 2 are important for records within 15 to 20 km of the causative earthquake. The parameters to be summarized are those defined by Somerville et al. (1997) and include those illustrated in Figure 1; additional parameters may be added based on the PEER data base update for the NGA project.

Structure of the DGML

It is planned that the basic structure of the DGML will be based on parameters of the seismic hazard environment. That is, records will be grouped or “binned” based on the earthquake source, travel path, and site conditions for the records. Currently, it is planned that records will be binned within the earthquake magnitude and closest source-to-site distance ranges shown in Table 3. Separate sets of bins will be formed for different site conditions (most likely “firm soil” and “rock” sets) and may be formed for different faulting mechanisms (strike-slip, reverse, normal). The overlapping of the two highest magnitude bins (6.5 - 7.0 and 6.9 - 7.9) is for the purpose of reducing the dominance of the M 7.6 Chi-Chi, Taiwan earthquake in the highest magnitude bin by including M6.9 recordings from the 1989 Loma Prieta, 1992 Erzican, and 1995 Kobe earthquakes in both bins. It is likely that the near-source bins will be defined as overlapping into the 10 to 25 km bin in order to bring in records with near-source ground motion characteristics as far as 15 to 20 km from the earthquake source.

Table 3
Preliminary Hazard Bin Ranges for DGML

Moment Magnitude	Earthquake Closest Source-to-Site Distance (km)
5.0 – 5.9	0 – 10, > 10 – 25, > 25 - 50
6.0 – 6.4	0 – 10, > 10 – 25, > 25 - 50
6.5 – 7.0	0 – 10, > 10 – 25, > 25 – 50, > 50 – 100
6.9 – 7.9	0 – 10, > 10 – 25, > 25 – 50, > 50 - 100

As discussed in the following section, sub-bins within the basic hazard bin structure may be formed for structural parameters or characteristics of interest.

Record Inclusion/Exclusion Criteria

A complete set of criteria for including records in, or excluding records from, the DGML, including the number of records in each bin, has not been finalized. Because of the importance of response spectral content and response spectral shape, it is planned to include as part of the criteria the shape of the spectrum of the recorded time history in comparison to the median shape for a particular hazard bin as determined by established ground motion attenuation relationships. The shape would be defined for a number of period ranges defined to encompass period ranges of interest for a wide range of structures. Sub-bins would be formed for record sets selected for each period range. Some records would be in multiple sub-bins. Preliminary period ranges selected for the sub-bins are shown in Table 4.

Within a given sub-bin, all records within the hazard bin (for example rock records in the magnitude range 6.5 - 7.0 and distance range 10 - 25 km) would be scaled to “fit” the median target spectrum calculated from attenuation relationships for the central magnitude and distance of that bin (for example M 6.75, distance 17.5 km). The fit for a given time history corresponds to equal differences of the record spectrum above and below the target spectrum. Then, a subset of records for the library (for the particular sub-bin) could be selected as some number of records having the closest overall “match” to the target spectrum. The closest match corresponds to the minimum mean of squared differences between the record spectrum and the target spectrum.

Table 4
Preliminary Period Sub-Bin Ranges For DGML
(seconds)

0.1 – 0.5	0.5 – 4
0.1 – 1.0	1 – 3
0.2 – 4.0	2 – 4
0.5 – 1.5	

Figures 2, 3, and 4 illustrate a trial application of this binning procedure for the period range 0.2 to 4.0 seconds within the rock record bin of M 6.5 - 7.0, distance 10 - 25 km. There are a total of 40 horizontal ground motion time histories within this hazard bin (before excluding any records). In Figure 2, the spectrum of the time history having the closest match to the target spectrum is compared with the target spectrum. The target spectrum was constructed using the Abrahamson and Silva (1997) attenuation relationship. In Figure 3, a similar comparison is made for the spectrum of the time history having the worst match. Figure 4 illustrates the selection of seven time histories that have the closest match to the target spectrum shape.

For application where the ground motion is defined on the basis of a probabilistic seismic hazard analysis (PSHA), the dominant (mean or mode) magnitude and distance would be determined by deaggregation of the probabilistic hazard, and the set of time histories having the closest match would be selected from the corresponding hazard bin and the sub-bin for a selected period range. These records would then be further scaled to the actual design spectrum determined from the PSHA.

There are many aspects to be decided with respect to the criteria for the DGML, including the total set of selection criteria to be applied and the details of the criteria. Certainly, within the near-source bins, criteria should include consideration of seismological directivity parameters (Figure 1). The overall goal is to form "representative" time history sets that, in aggregate, are representative of the expected or average hazard conditions for a project site.

Where it is desired that a broad range of potential variability be included in a selected record set, consideration can also be given to including randomly selected records from the hazard bins.

Utilization Guidelines

Table 5 summarizes topics for which utilization guidelines will be developed for scaling records to be the level of the actual design response spectrum after record sets have been selected. There are two types of scaling: (1) simple scaling by a constant factor; and (2) spectrum matching using techniques that adjust the frequency content of a time history so that the spectral peaks and valleys of the record are largely eliminated and the resulting spectrum is a close fit to a smooth design spectrum. There are pros and cons to each type of scaling and advocates for each. Both types of scaling will be covered in the guidelines with the pros and cons indicated and the procedures for implementation of the topics in Table 4 described in detail. PEER and PEER-Lifelines Program have been and are investigating these topics. For example, Shome et al. (1998) and Cornell (2003) reported on the insensitivity of inelastic response to varying amounts of simple scaling of records to the level of the design spectrum, and Carballo and Cornell (2000) and Bazzurro and Luco (2003) have conducted studies that indicate that spectrum matching biases inelastic response somewhat to the low side in comparison to response using simple scaling. Such studies will be further considered during the development of utilization guidelines.

Table 5 Topics for Utilization Guidelines for the DGML, Simple Scaling and Spectrum Matching Approaches
▪ **Simple scaling approach (by constant factor)** - guideline limits on scaling factors - number of records - guidelines on aggregate "match" of scaled record parameters to design values - guidelines for scaling records for 2-component or 3-component dynamic analysis

▪ **Spectrum matching approach**
- advantages and limitations of spectrum matching versus simple scaling
- guidelines for the spectrum matching process
  - similarity of spectrum shape of record and design spectrum
  - scaling before matching
  - acceptable spectrum matching methods (frequency and time domains)
  - tolerances for spectrum matching fit and number of periods for evaluating
- number of records

Summary

Evaluations to date by the project team indicate that binning of records for the DGML should principally be based on seismic hazard (as principally indicated by earthquake magnitude and distance ranges and site conditions). The evaluations also indicate that with the current state of knowledge, an important criterion for selecting subsets of records for the DGML within defined hazard bins should be the elastic response spectral shape over a period range of significance for a specific structure. Work to date has tentatively defined hazard bins and a procedure for selecting record subsets that, when scaled, will have response spectral shapes that are most consistent with a target spectrum shape that is representative of the hazard bin.

Within near-source distances (say within 15 km to 20 km of the earthquake source), record selection criteria should also include the time-domain pulsive characteristics of records and earthquake rupture directivity conditions that produced the near-source ground motion characteristics. Both within and outside the near-source region, it is currently not clear which ground motion characteristics other than the characteristics mentioned above should comprise part of general DGML record selection criteria. However, duration of shaking and inelastic response spectral characteristics appear to be ground motion characteristics that warrant consideration.

The difficulties of using many ground motion parameters as part of the general record selection criteria are, at present, two-fold: (1) the importance of the parameter to structure damageability may not be clear, and the knowledge is evolving; and (2) ground motion attenuation relationships to predict the values of those parameters as a function of the seismic hazard environment (e.g., magnitude, distance, local site conditions, etc.) have not yet been developed for most of the parameters in Table 1, thus it may not be clear what constitutes a "high", "low", or "average" parameter value for a given seismic environment. Nevertheless, further consideration will be given to how other time history characteristics may be incorporated into record selection criteria.

It is straightforward to quantify for individual time history records many of the ground motion parameters of potential interest to a designer for a specific project (e.g. parameters listed in Table 1). For records placed in the library, it is planned to quantify many of these parameters, as selected by the project team members and reviewed by advisors representing CSMIP and PEER-Lifelines Program, so that these characteristics of records can be considered by users of the library, whether or not the parameters are part of general record selection criteria.

Detailed guidelines will be developed for using the DGML to assemble and scale record sets for applications. Scaling approaches to be addressed include simple scaling and spectrum matching. The topics listed in Table 5 will be addressed in these utilization guidelines.

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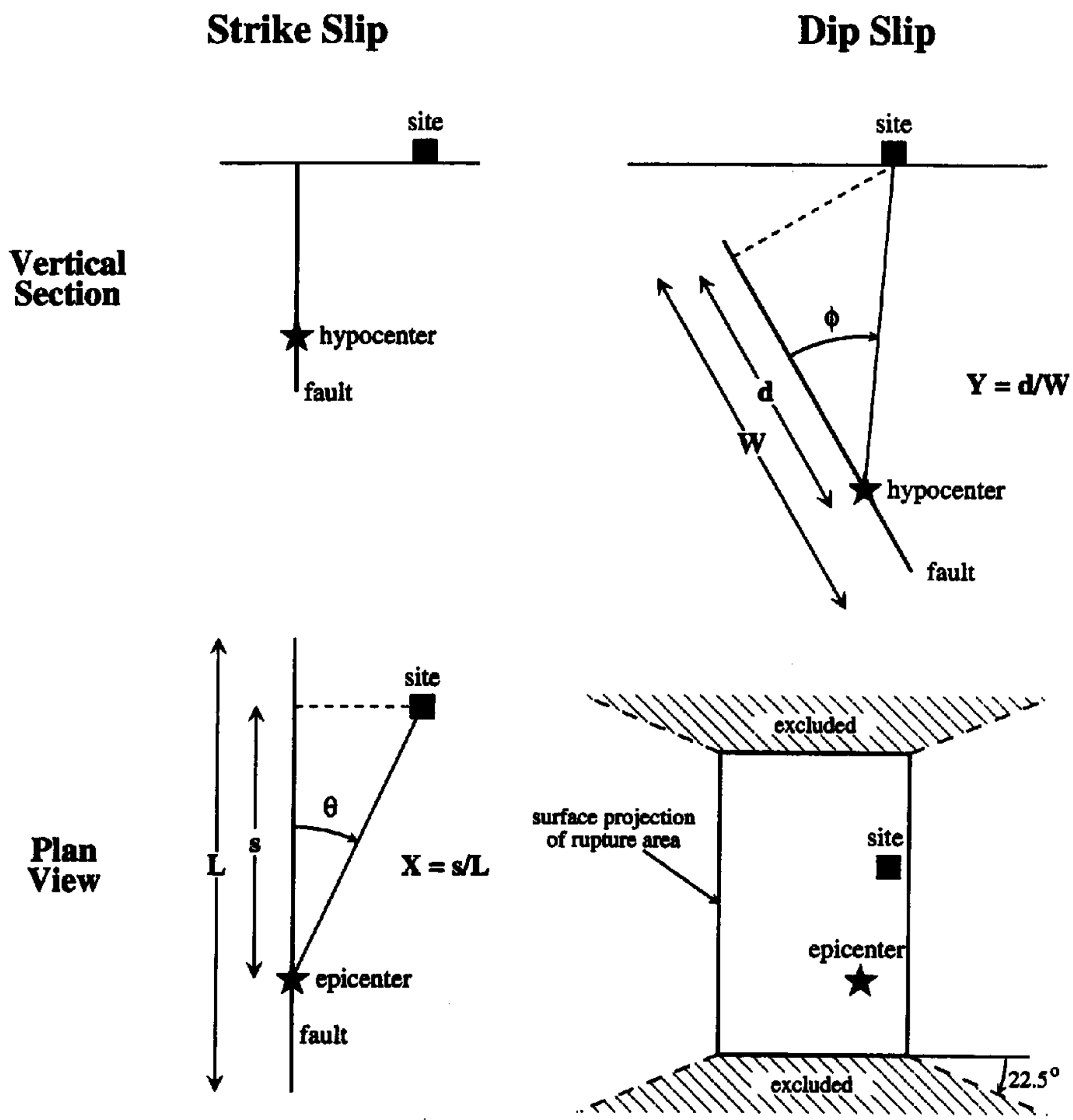

Figure 1 Definition of rupture directivity parameters Θ, s, and X for strike-slip faults, and Ø, d, and Y for dip-slip faults, and region off the end of dip-slip faults excluded from the model (Somerville et al., 1997).

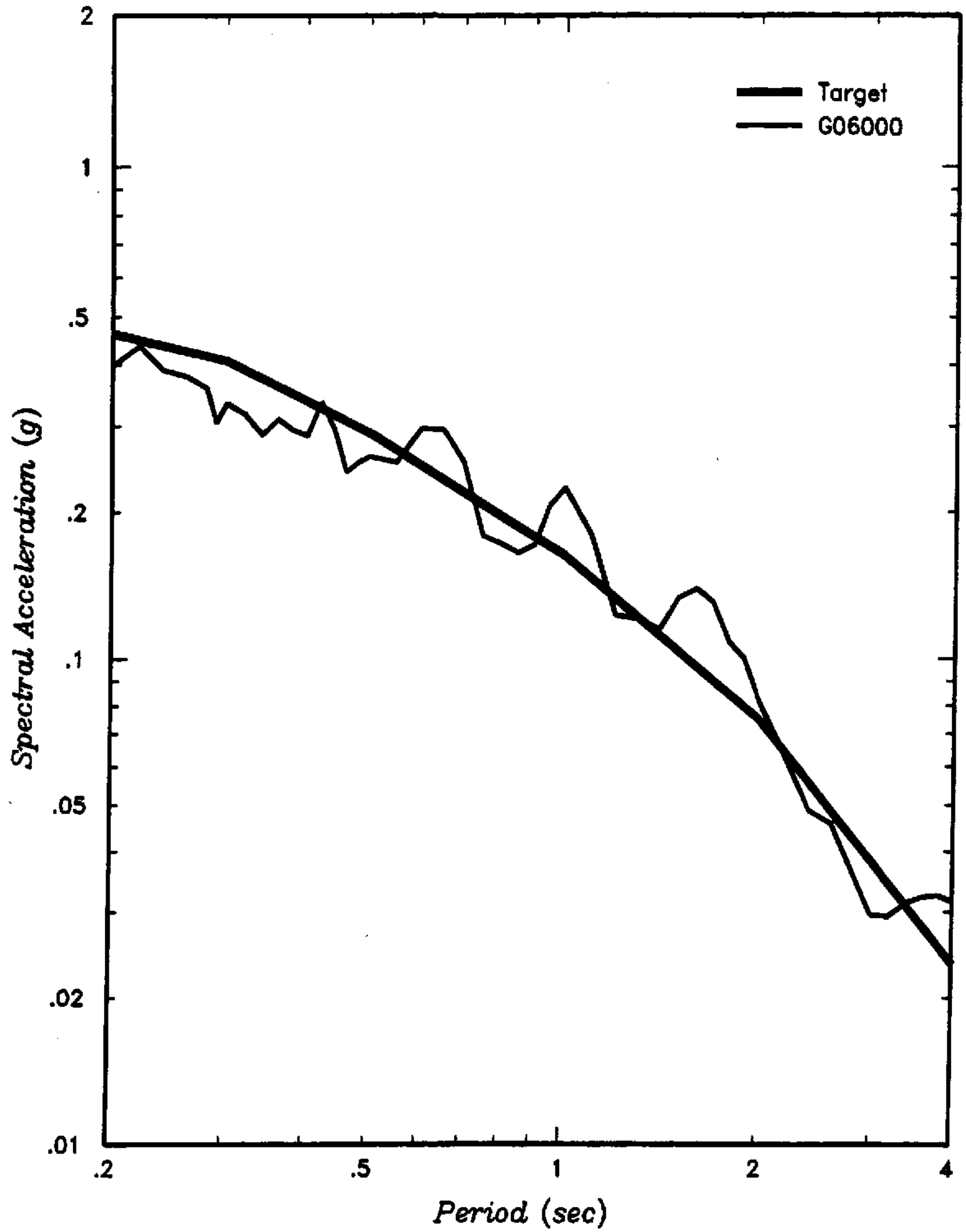

Figure 2 Horizontal component having closest "match" to target spectrum shape for hazard bin M 6.5-7.0, distance 10-25 km, rock.

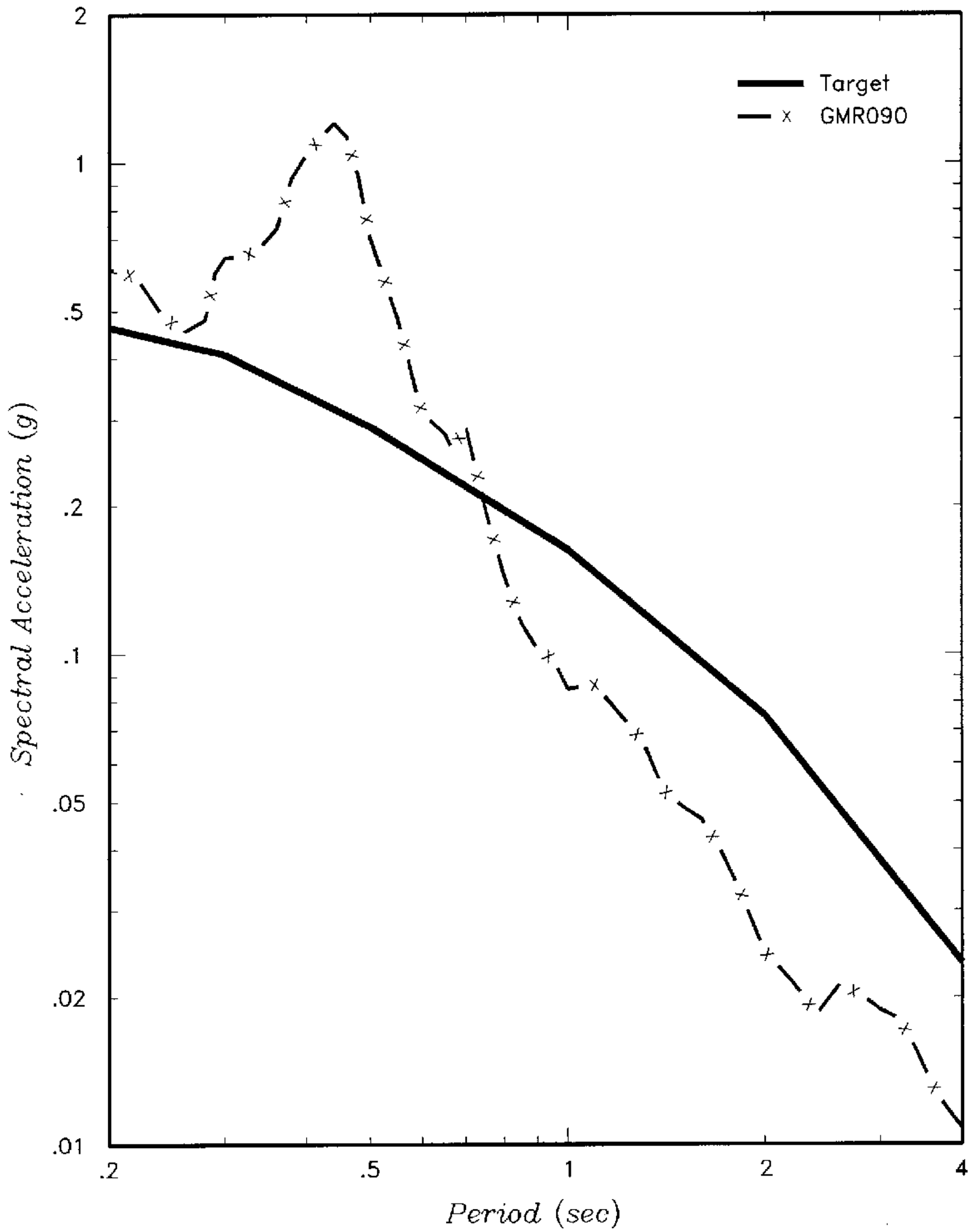

Figure 3 Horizontal component having worst "match" to target spectrum shape for hazard bin M 6.5-7.0, distance 10-25 km, rock.

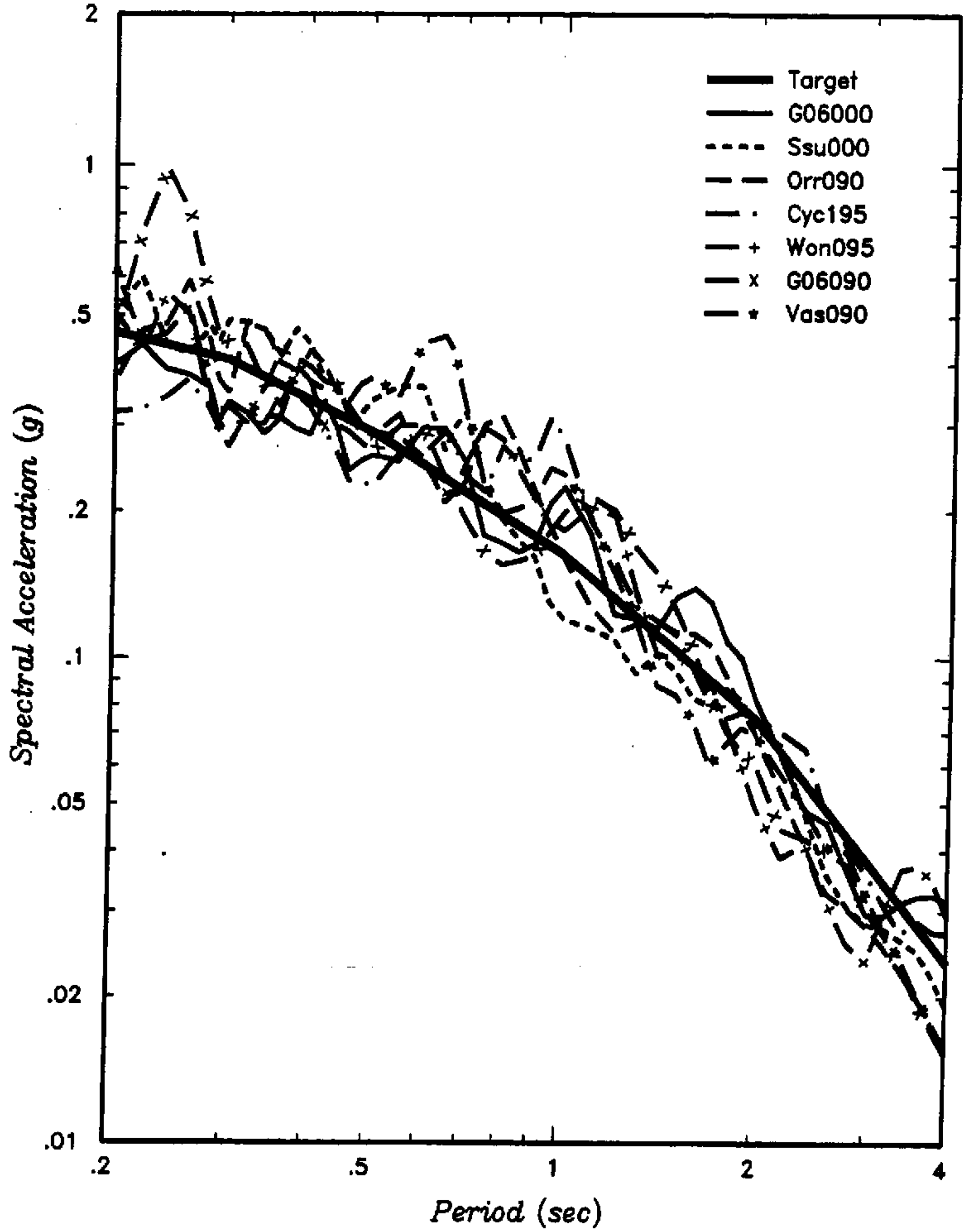

Figure 4 Seven horizontal components having closest "match" to target spectrum shape for hazard bin M 6.5-7.0, distance 10-25 km, rock.