An Improved Approach for Ground Motion Suite Selection and Modification for Use in Response History Analysis

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SUMMARY

When selecting ground motions for use in response history analysis, design codes such as ASCE 7 and the IBC require that the average of the spectrum resultant, either the SRSS or the fault-normal component, of the selected suite of ground-motion pairs exceed a target design spectrum over a specified period range. Because the design spectrum used to select and modify the ground motions is based on the seismic-hazard characteristics of the site, it is important that the ground motions used in the simulation are modified such that these characteristics are preserved as much as possible. The simple method of amplitude-scaling the ground motions to meet the design code achieves this goal. However, there may be cases where the required amplification, or de-amplification, of the ground motion may vary significantly from the preferred scale factor of 1.0. Amplitude-scaling may also lead to average response spectra that vary significantly in shape from that of the design spectrum in certain period ranges. This may lead to undesirable outcomes such as unrealistic amplification of higher-mode response.
The procedure proposed in this paper modifies the frequency content of the ground-motion suite to ensure that the average of the spectrum resultant closely matches the design spectrum at all periods. Because the matching is done at the spectrum-resultant-average level, the required modifications are small compared to the conventional method of spectrally matching every record. This process significantly reduces the higher-mode amplification effects frequently present in the usual amplitude scaling method. In addition to matching a target average spectrum, the procedure can also be extended to achieve a target spectral acceleration standard deviation versus period as well.
The proposed approach also differs from so-called tight spectral matching, where both components of all record pairs are tightly spectrally matched to the design spectrum and the record characteristics and record-to-record variability are lost. In the proposed procedure the matching is done only at the level of the average spectrum, and so each ground-motion component still maintains its characteristic variation of spectral acceleration with period. The implementation of this methodology and its effects on design will be presented.

Keywords: Spectral Matching, Ground Motion Selection Scaling Modification

1. INTRODUCTION

When selecting ground motions for use in response history analysis, design codes such as ASCE 7 and the IBC require that the average of the spectrum resultant, defined as either the SRSS of the pair or the fault-normal component, of the selected suite of ground-motion pairs exceed a Target Spectrum over a specified period range. The Target Spectrum is defined as the Design Spectrum amplified by a code-specified factor. Because the design spectrum used to select and modify the ground motions is based on the seismic-hazard characteristics of the site, it is important that the ground motions used in the simulation are modified such that these characteristics, such as amplitude, frequency content and duration, are preserved as much as possible.

With no restriction on the number of records in the suite, it is possible to achieve the goal of matching the target spectrum on average with simple amplitude scaling. If limits on scale factors are applied in the process, the resulting ground-motion suite is able to represent the site hazard accurately. Additional algorithms can be implemented in the selection and scaling to also control the variance in these ground motions within the suite (Jayaram 2011).

Design codes, however, allow a minimum of three appropriate ground motions. When three ground motions are used, the maximum response is considered in the design, when seven or more ground motions are used, the average response is considered (ASCE, 2010). Because of the large number of load and model combinations that often need to be evaluated, it is not practical to run an unlimited number of records. Because of these constraints, ground-motion suites are handled in either two ways in engineering practice – amplitude scaled or spectrally matched.

When amplitude scaling is employed, the ground motion record pairs in a suite are scaled individually to meet a specific criterion, such as scaling to the target-spectrum ordinate at a specific period or to minimize the Mean Squared Error over a specified period range. In addition, the suite is scaled as a group to meet the code requirement of exceeding the Target Spectrum over a specified period range. When spectral matching is employed in the traditional sense, each individual ground-motion record is modified in the time or frequency domain such that its response spectrum closely matches the target spectrum within a specified period range. These two methods have been extensively studied in the literature (Heo, 2011).

The alternative procedure proposed in this paper modifies the frequency content of the ground-motion suite to ensure that the *average* of the Spectrum Resultants closely matches the Target Spectrum in the specified period range. Because the matching is done at the Spectrum-Resultant-average level, the required modifications are small compared to the conventional method of spectrally matching every record component. This process significantly reduces the higher-mode amplification effects frequently present in the amplitude scaling method while still maintaining the desired record-to-record variability as well as the jaggedness of each individual response spectrum, which are lost in spectral matching. In addition to matching a target average spectrum, the procedure has been extended to achieve a target spectral acceleration standard deviation versus period as well.

2. AMPLITUDE SCALING & TIGHT SPECTRAL MATCHING

When the number of ground motions in a suite is limited to a finite set, it is difficult to control the average response spectrum over a wide period range and even more difficult to constrain the variability of the records over this period range, as demonstrated for the suite of 10 records shown in Figure . Traditionally, this limitation has been overcome by employing spectral matching techniques to the ground-motion suite, as shown in Figure . The two figures highlight the advantages and disadvantages of the two techniques.

Amplitude scaling has several advantages resulting from the fact that the only modification applied to the records is an amplitude scaling. The records in an amplitude-scaled suite maintain all individual characteristics of the original record (except amplitude). The characteristic period and energy content of the record are maintained, as is the variability between periods and records. The peaks and valleys that are maintained in the individual response spectra can be beneficial to the nonlinear response of the structural model, as well as be more realistic.

As shown in Figure , however, meeting the code can lead, on average, to high energy content at higher modes. When using a limited number of records, each record can influence the mean significantly and the dispersion at each period can be significantly large. Meeting the code can also lead to unreasonable scale factors with significant amplification or deamplification. There may be records in the resulting suite with unrealistic spectral-acceleration values, which can be as high as 5g. Because each record has a strong influence on the suite scaling, this method is highly sensitive to the selection of ground motions for the suite as well as to the scaling criteria and good selection is important.

Traditional tight spectral matching was developed to address the limitation of amplitude scaling. Because it modifies each record component to the target spectrum, the characteristics of the suite are independent of the ground-motion selection. The method minimizes potential amplification of higher modes but significantly reduces the variability in spectral ordinates. This meets the code goal of evaluating the mean response but is inappropriate where variability must be considered in the design process. This is presently required as an exception by ASCE 7-10 for design of certain building components for omega-level design forces where maximum response needs to be considered (Section 16.2.4.1)

The main criticism of spectral matching is that it generates unrealistic records. The modification is significant enough to lose the characteristic frequency content of each record, resulting in the same energy content over all records. There is also no variability between records in terms of elastic response spectra. The loss of peaks and valleys along the period spectrum is expected to yield unrealistic results. In addition, scale factors are often neither recorded nor considered.

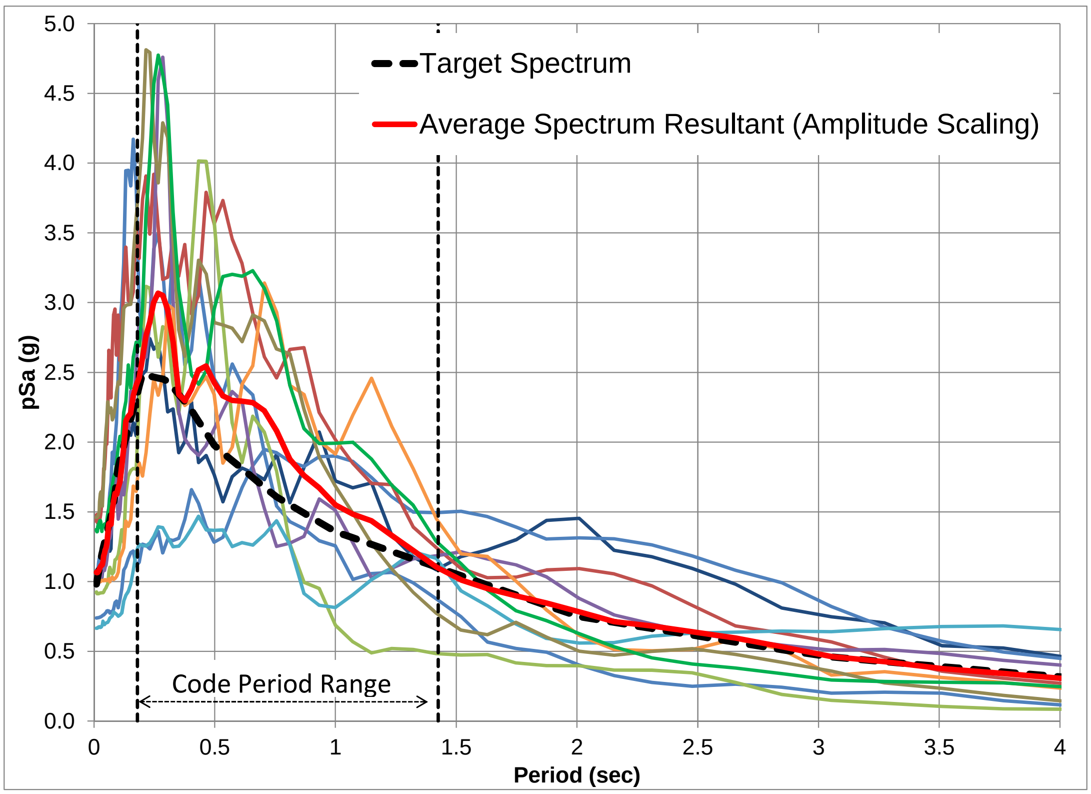

Figure 1 Amplitude-Scaled Ground-Motion Suite

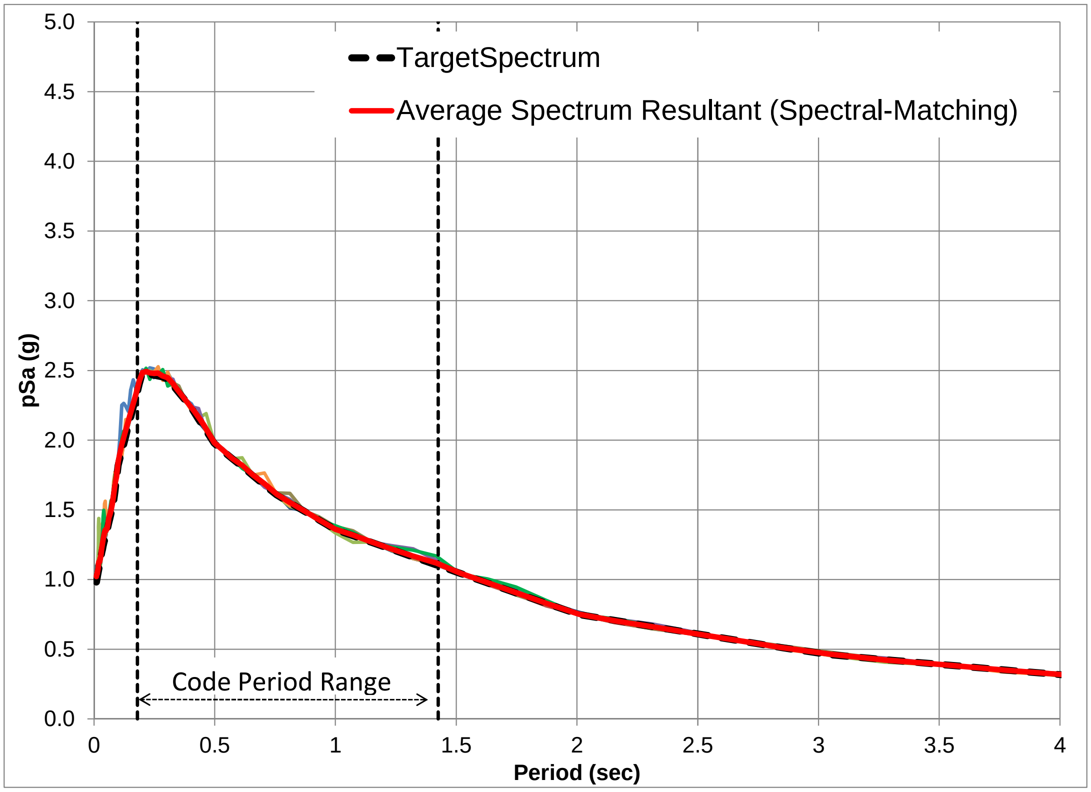

Figure 2 Spectrally-Matched Ground-Motion Suite

3. MEAN SPECTRUM MATCHING

An alternative method of ground-motion suite management, Mean Spectrum Matching, has been developed by the authors to address what is relevant to the structural engineer by minimizing the limitations of the two traditional methods. The method has been reviewed and approved by CGS (California Geological Survey) & OSHPD (Office of Statewide Health Planning and Development) for use on a new-hospital design project.

The objective of this methodology is to scale and modify the ground motions such that the average Spectrum Resultant (SR), defined as the SRSS or the Fault-Normal component, matches the Target Spectrum in the code-specified period range, as shown in Figure 3. As shown in the figure, the peaks and valley of the individual records are preserved, as are the characteristic period and energy content. This method reduces the peaks of the individual spectra and, therefore, minimizes the amplification effects on higher modes. This method minimizes the record modification, thus maintaining the record characteristics and controlling the variability while meeting the code requirements. As shown in Figure 4 and Figure 5, the damped elastic response spectrum and acceleration history of the modified records, respectively, do not differ significantly from the original records.

Mean Spectrum Matching is a multi-step process. In the first step, each ground-motion pair is individually scaled to meet a specified criterion on the Spectrum Resultant, as shown in Figure 6. The second step in the process is to apply an additional scale factor to the entire suite such that the Mean Squared Error between the average of the Spectrum Resultants and the Target Spectrum is minimized, as shown in Figure 7. The records are subsequently modified such that the average of the scaled and modified Spectrum Resultants equals the Target Spectrum in the specified period range, as shown in Figure 3. For near-field sites, different modification targets can be used on the two orthogonal components such that the averages, and targets, in the two directions are different.

When using the Mean Spectrum Matching algorithm, the engineer can also take an additional step to control the record-to-record variability at different periods, as shown in Figure 8. In the limit, when the variability (coefficient of variation) is set close to zero, the method can reproduce tight spectral matching.

An important step in the Mean Spectrum Matching process, as well as in the Amplitude-Scaling process, is criterion defining the initial scaling of the individual ground-motion records. Typical criteria include scaling to the target spectral ordinate at a specified period – either at zero period (peak ground acceleration) or at the fundamental period of the structural model. The most-commonly used method is to scale the records to minimize the Mean Squared Error (MSE) of each record with respect to the Target Spectrum. Scaling to minimize the MSE is typically the preferred method because it gives an initial spectrum that is closest to the target spectrum. Such scaling, however, can lead to individual records with significantly-large localized spectral acceleration values, especially after the entire suite has been scaled to meet the design requirements, as shown in Figure 9. The authors recommend specifying a criterion such that the individual Spectrum Resultants are enveloped by the Target Spectrum, as shown in Figure 6. By constraining the individual spectra inside the envelope, the recommended method leads to less dispersion in the spectral peaks, even when only amplitude scaling is employed, as shown in Figure 1. Figure 10 also demonstrates a reduction in the resulting average spectrum for such a case.

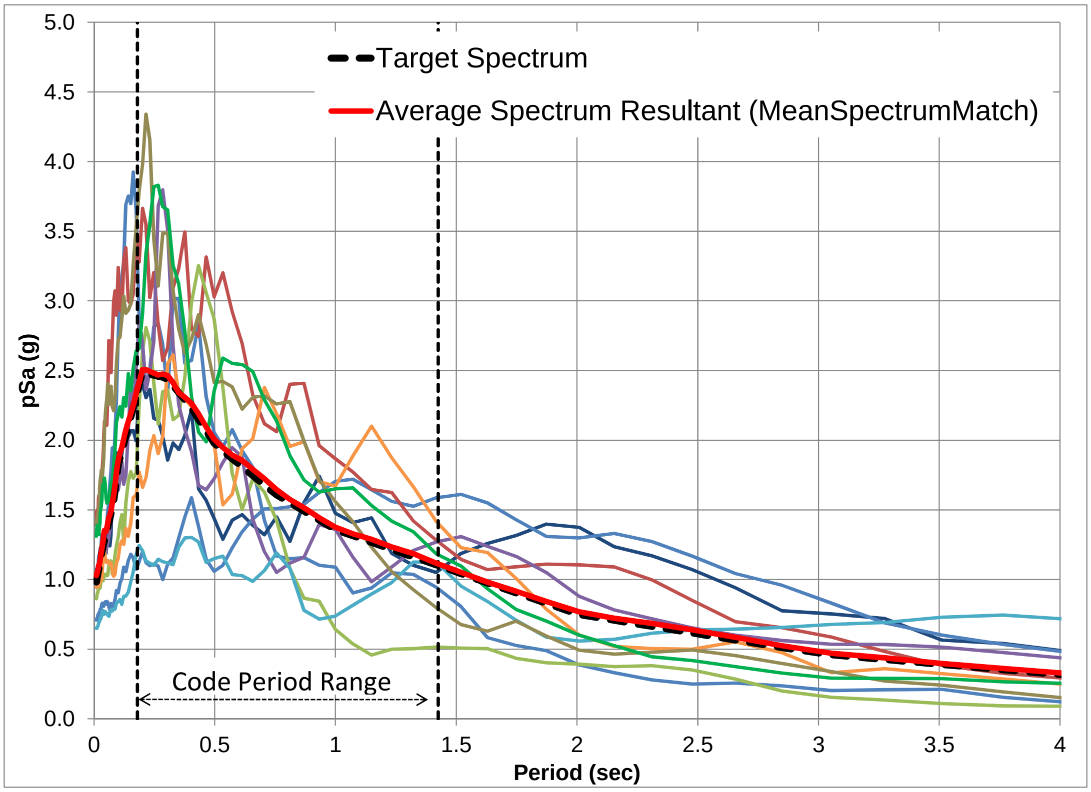

Figure 3 Mean-Spectrum-Match Modified Ground-Motion Suite

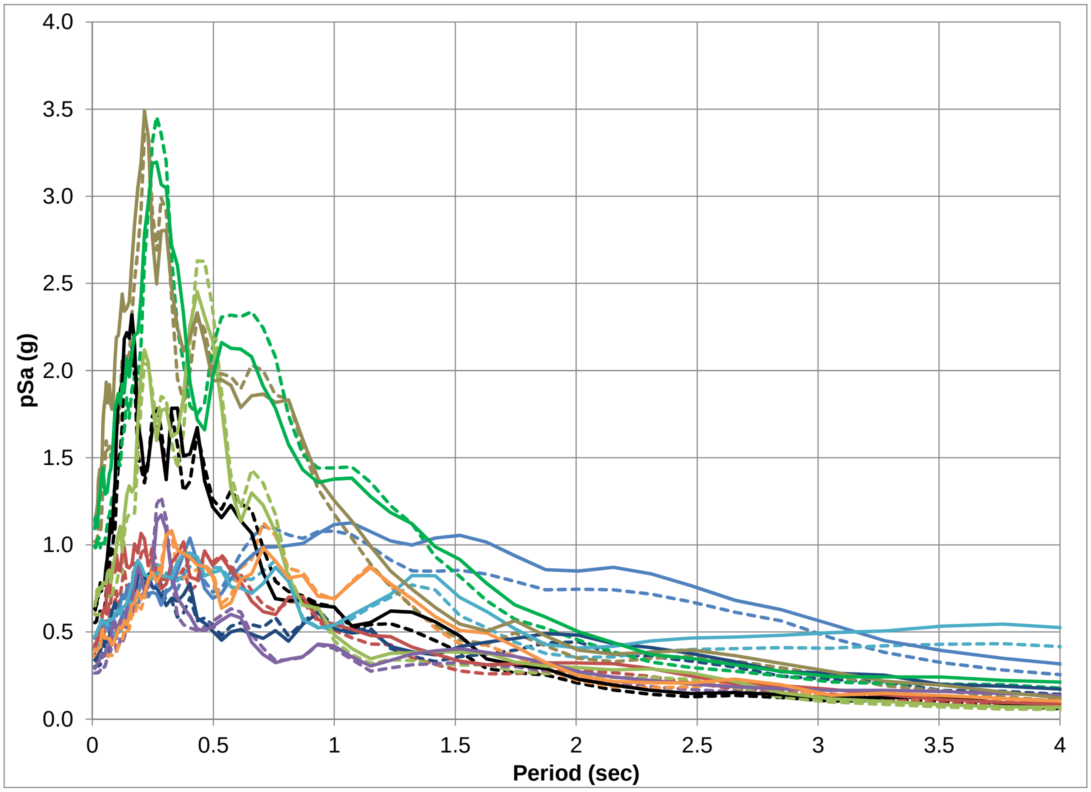

Figure 4 Original and Modified Damped Elastic Response Spectra

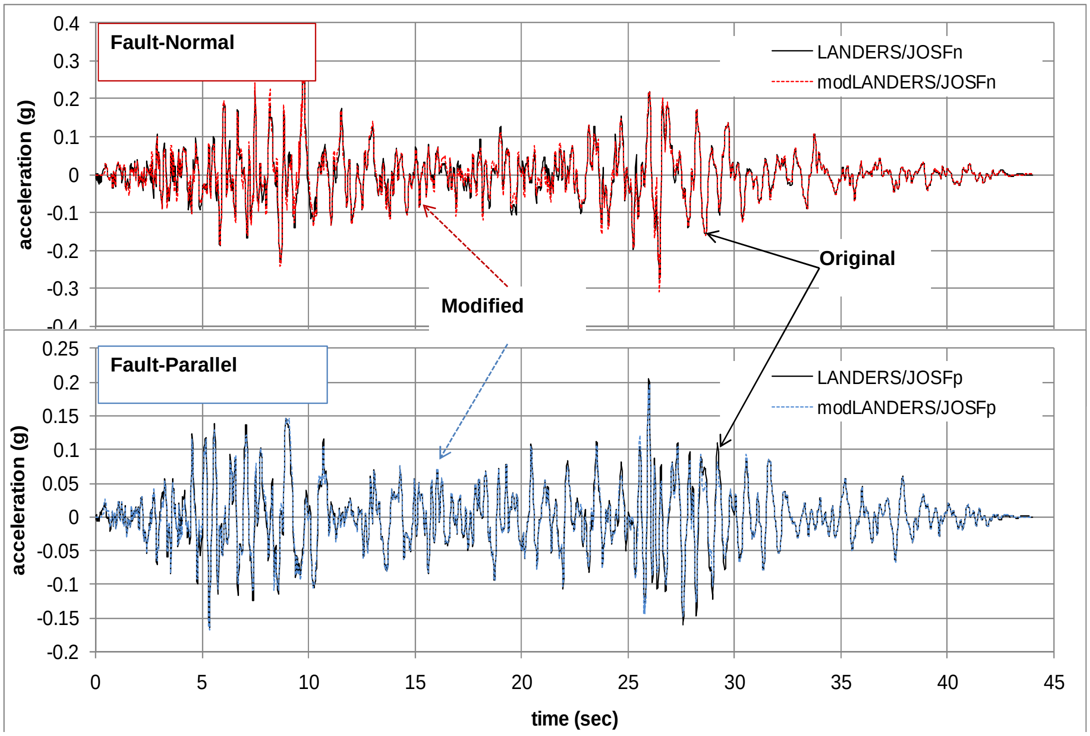

Figure 5 Original and Modified Elastic Response Acceleration Histories

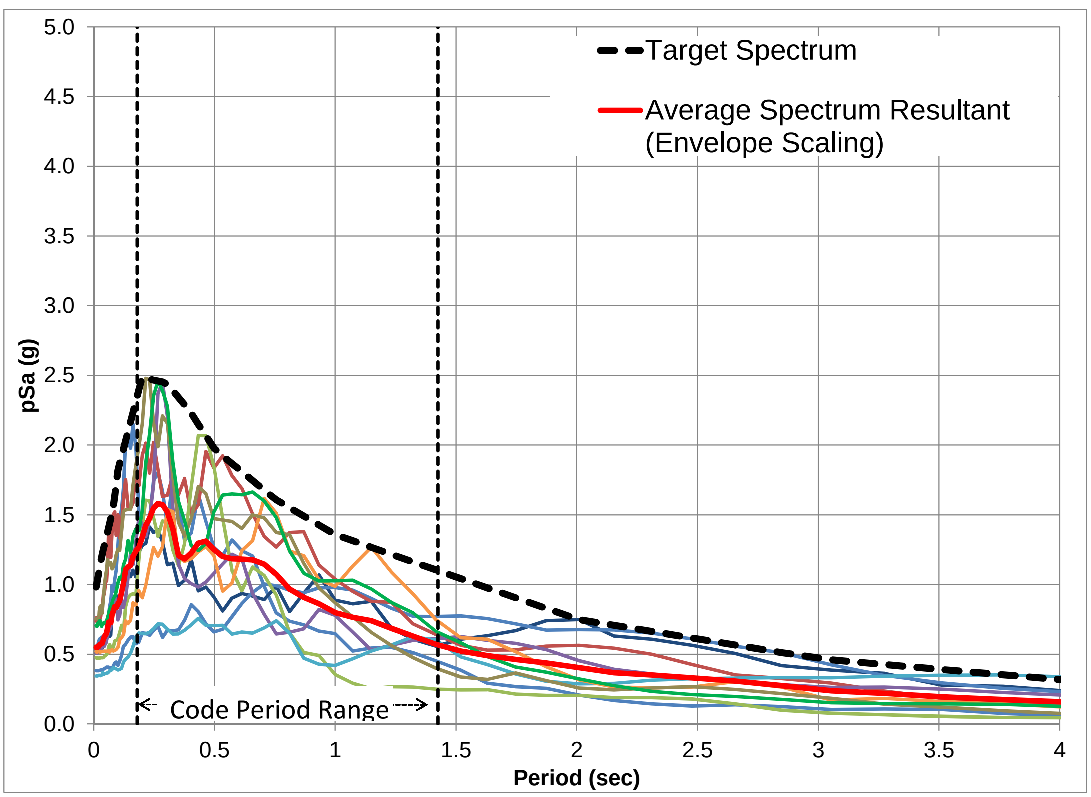

Figure 6 Record Scaling to Target-Spectrum Envelope

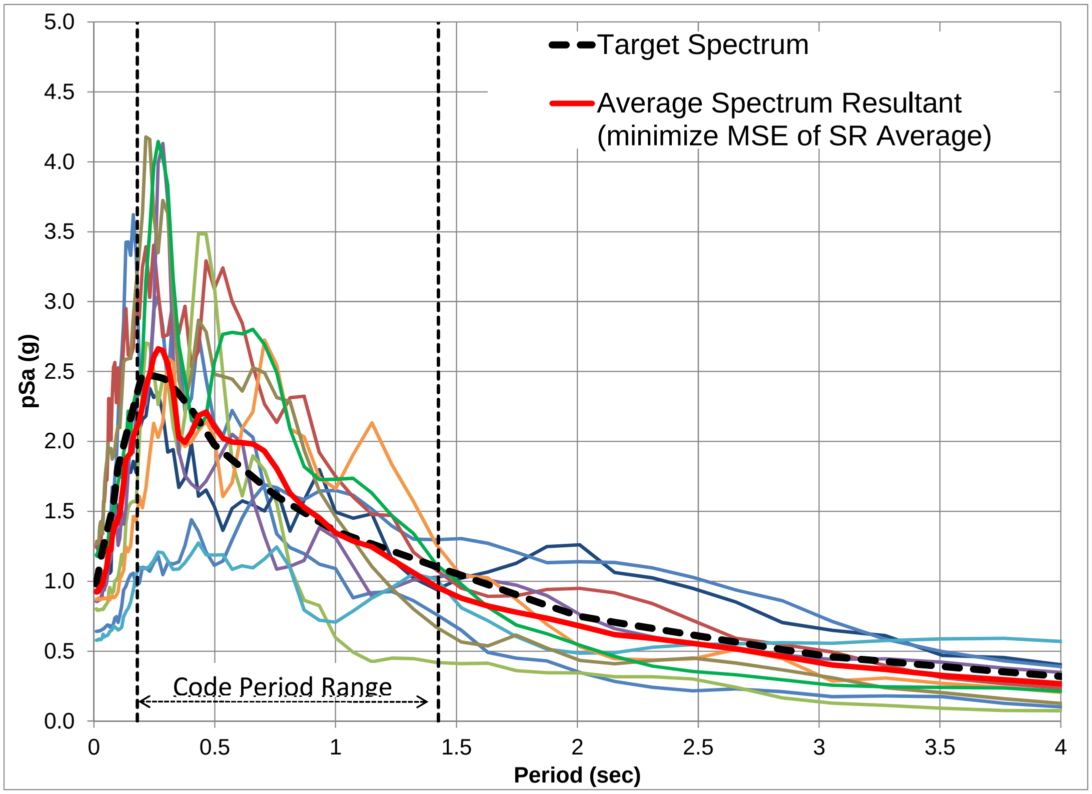

Figure 7 Scale Suite to minimize MSE of Average SR with respect to Target Spectrum

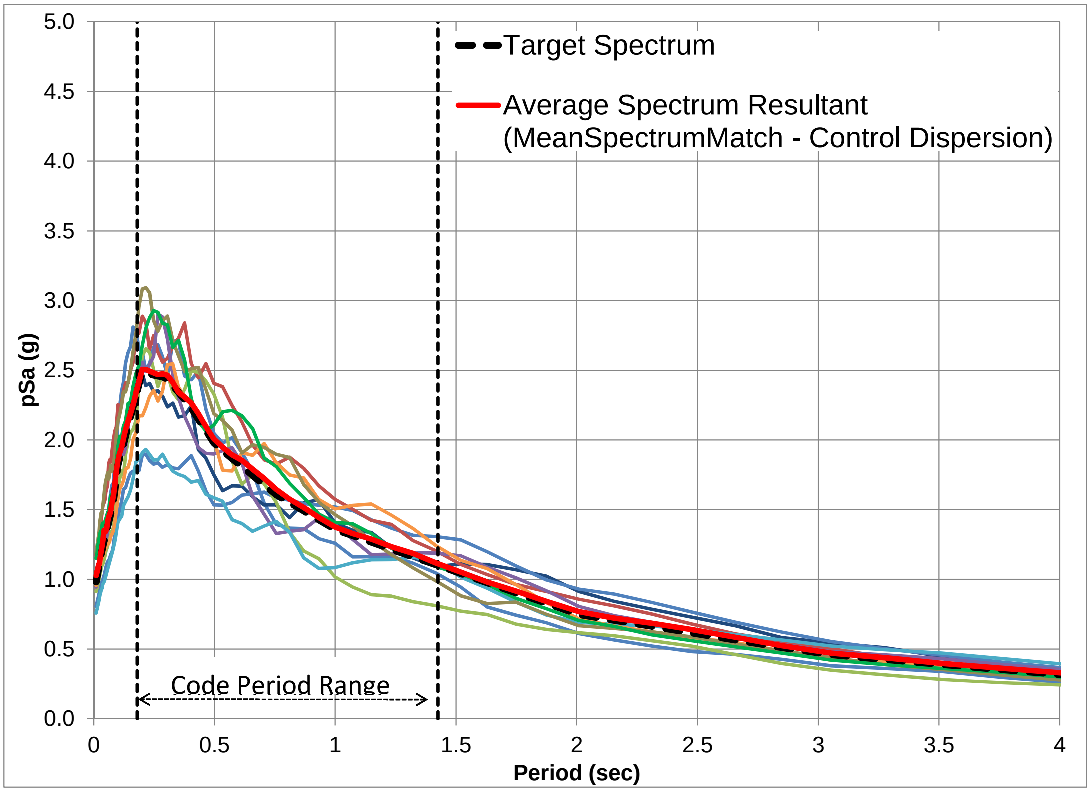

Figure 8 Mean Spectrum Matching + Dispersion Control

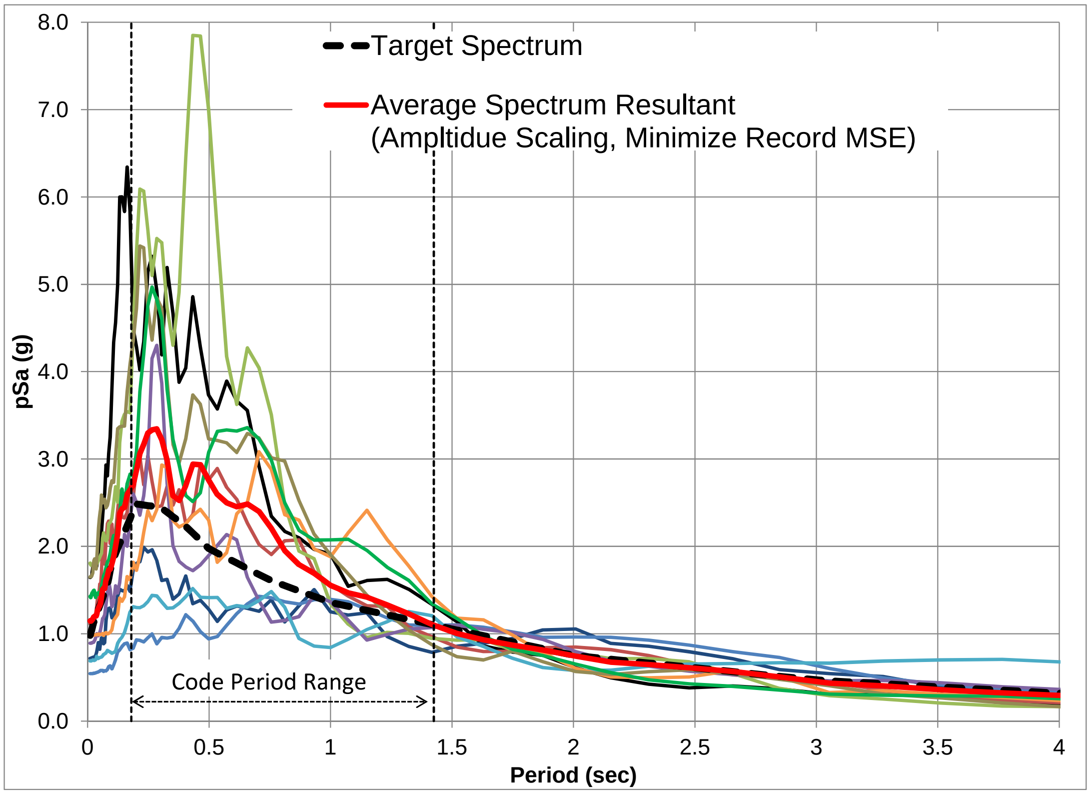

Figure 9 Amplitude-Scaled Suite using Minimization of MSE for each Record as Initial Scaling Step

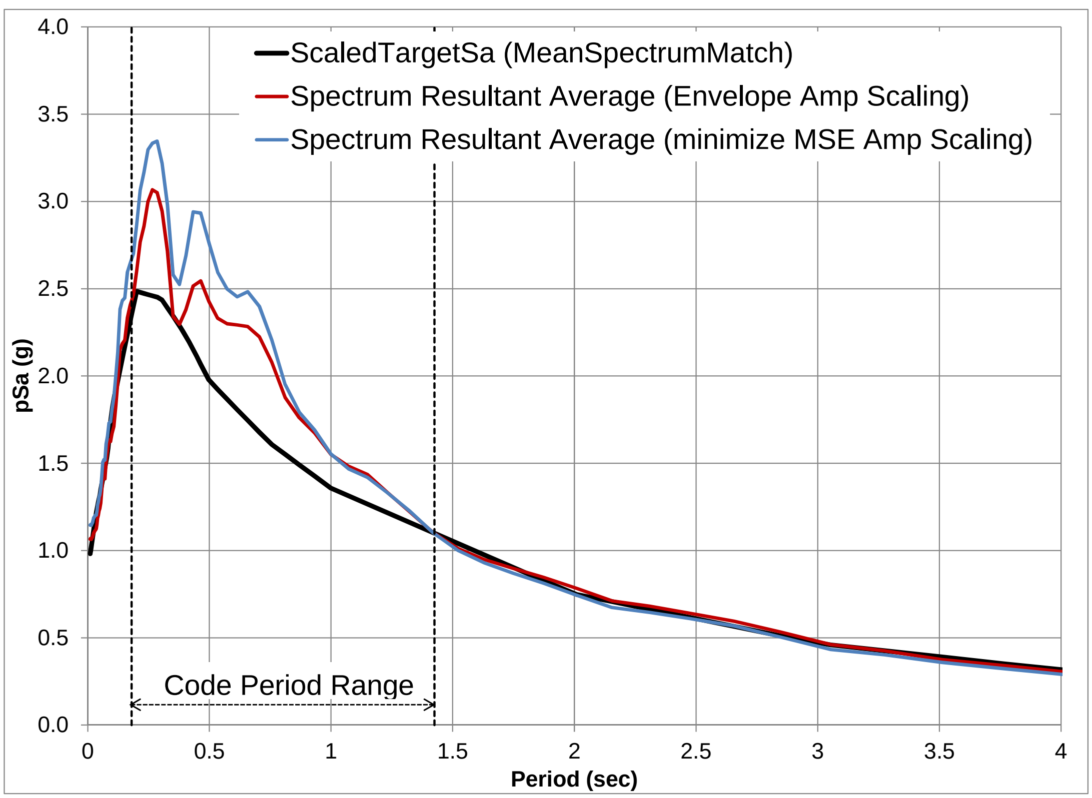

Figure 10 Comparison of SR Average for Different Amplitude-Scaling Methods

4. CONCLUSIONS

The method of Mean Spectral Matching presented in this paper is a practical tool for ground motion selection and modification. By matching the target spectrum on average, the method minimizes the amplification and modification to the ground-motion records. It preserves the advantages of amplitude scaling, such as maintaining the dynamic characteristics of the individual record, as well as those of spectral matching, such as a minimizing the amplification of higher modes and meeting the code criteria for the suite as a whole. Most importantly, the method enables control over the dispersion of spectral acceleration between records at both scaling and modification steps.

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