Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

EFFECTS OF TIME-DOMAIN GROUND MOTION SCALING METHODS ON THE NONLINEAR RESPONSE OF A REINFORCED CONCRETE RESIDENTIAL TOWER

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ABSTRACT

A high-rise reinforced concrete tower with 56 stories in Tehran is evaluated for its performance against seismic demands according to FEMA 356. The tower consists of three transverse shear walls which are the main walls, and several side walls perpendicular to each main wall. A nonlinear dynamic model is developed and analyzed using seven pairs of ground motions as recommended by FEMA 356. The ground motion records are selected based on site parameters and hazard analysis, and are modified by the ratio of site representing peak ground acceleration (PGA) to the PGA of their major components. The selected pairs of ground motions are scaled such that their average spectrum matches the site specific spectrum. Scaling is done in the time domain and using 3 different recommendations which are based on the optimization approach, uniform scaling and physical approach respectively. The consequences of each method are studied according to the shear deformation of main wall panels and the drift response of the structure.

Introduction

A 56-story reinforced concrete tower in Tehran is evaluated for its seismic performance using nonlinear dynamic analysis according to FEMA 356. The tower consists of three transverse main shear walls with angles of 120 degrees and several side walls perpendicular to each main wall (Fig. 1).

In a dynamic time-history analysis, several ground motions recorded in similar sites (similar magnitude, fault distance and source mechanism) are used. In fact, none of them is the real one on which our structure should resist. The site specific spectrum which is a result of site characteristic studies and hazard analysis, so far, is known as the best representer of the specifications of the site. Then the ground motion records should be modified so that their spectrum matches with the site specific spectrum. According to FEMA 356, each record shall be scaled in the time domain such that the average value of the square root of the sum of the squares (SRSS) spectra does not fall below 1.4 times the 5%-damped site specific spectrum for periods between 0.2T seconds and 1.5T seconds (where T is the fundamental (translational) period of the building).

There are many different scaling methods in the time and frequency domains but none of them is recommended by some practical codes or standards. On the other hand, in a real exercise, a decision should be made to use one appropriate method of scaling. Perhaps using a constant scaling factor for all of the records seems to be the most general alternative but with unequal factors, more coincidence

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with the site specific spectrum is attainable.

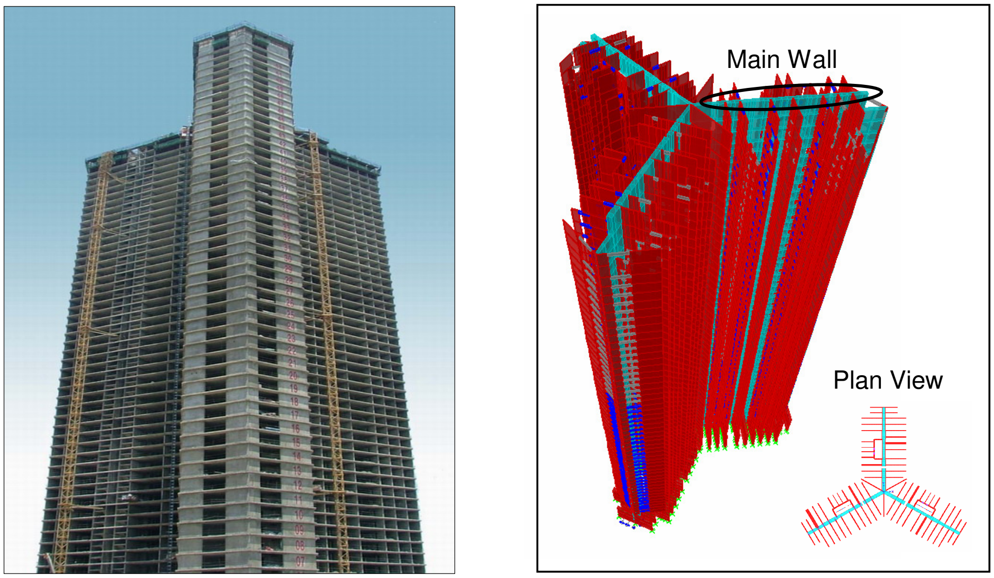

Figure 1. Tehran tower view (left), 3D nonlinear model of the tower (right).

In this project, we have studied three time domain scaling methods which are based on the optimization approach (Naeim and Bhatia 2000), uniform scaling and physical approach (Kircher 1996) respectively. The consequences of each method are studied according to the shear deformation of main wall panels and drift response of the structure.

Site Specific Spectrum and Ground Motion Records

Seven pairs of ground motions are selected. The site specific spectrum is developed according to the site characteristic studies conducted by the team in charge. Also the site specific PGA is proposed to be 0.37g. Selected ground motions are firstly scaled by the ratio of the site specific PGA to the PGA of their major component. Strong motion duration of each record is calculated using its Husid plots (Brady and Trifunic 1975). Table 1 shows the properties of the records.

Table 1. Properties of each pair of ground motion records.

Record	PGA (g)	Duration (s)
GM1 component 1	0.370	10.82
GM1 component 2	0.326	11.24
GM2 component 1	0.370	8.39
GM2 component 2	0.298	9.22
GM3 component 1	0.370	11.58
GM3 component 2	0.259	12.45
GM4 component 1	0.370	5.52
GM4 component 2	0.366	5.90
GM5 component 1	0.370	13.20
GM5 component 2	0.356	12.39
GM6 component 1	0.370	15.37
GM6 component 2	0.362	16.81
GM7 component 1	0.370	10.61
GM7 component 2	0.286	15.64

The 5% site specific spectrum is shown in Fig. 2. The SRSS of 5% damped spectra for each pair of ground motion records and the average of them (average spectrum) are also shown.

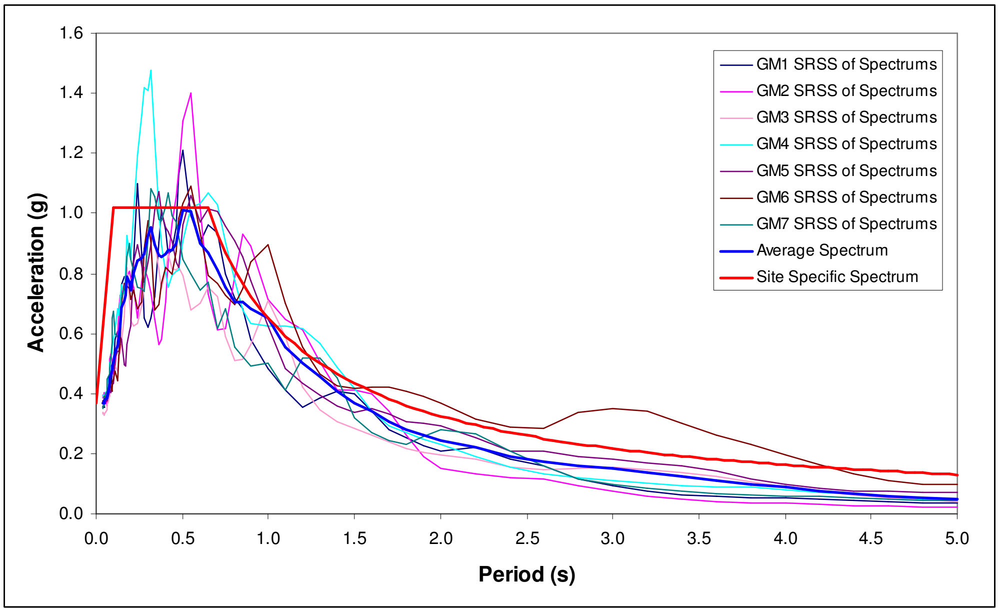

Figure 2. 5%-damped site specific spectrum, 5%-damped spectrum of ground motion records, average of spectra of records.

The first mode of the structure is the torsional mode with the period of 3.8 s, and the fundamental translational period that is 1.3 s corresponds to the second mode.

Scaling Factor Calculation

Three methods of ground motion scaling are used in this study. Details of the methods are given in Appendix 1 and Appendix 2.

Scaling by Optimization Approach

This approach minimizes the difference between site specific spectrum and average spectrum (Alimoradi et al. 2004). It calculates all scale factors such that the average spectrum has the highest possible coincidence with the site specific spectrum. In other words, the site specific spectrum is supposed to be the comprehensive representer of the site and the base of scaling the records. In fact, the records whose spectrum is more similar to the site specific spectrum are less modified.

Here, the method of time domain scaling via nonlinear programming (Naeim and Bhatia 2000) is used. This method tries to keep the scaling factors as near as possible to each other and simultaneously minimize the difference between site specific spectrum and average spectrum.

This method is implemented using the Genetic Algorithm Toolbox of MATLAB and the results are presented in Table 2 (Here, $\boldsymbol{\tau}$=1.23 and $\mathbf{Z}_{\mathbf{min}}$=3.46 for $\mathbf{m}$=1.4, see Appendix 1)

Table 2. Scaling factors based on the optimization approach.

S_1	S_2	S_3	S_4	S_5	S_6	S_7
1.29	1.01	0.95	1.49	1.40	1.22	1.36

Uniform Scaling

In this method, the principle is to keep the effect of all records uniform. In other words, all of the records are supposed to have the same priority and importance. This is the simplest method in which the smallest factor which moves the average spectrum over the site specific spectrum (See Fig. 2) in the given range of periods is selected as the scale factor and will be uniformly applied to all of the records. Using this method, the uniform scale factor is 1.27.

Scaling by Physical Approach

In this approach, the physical characteristics of the records are respected. Here we use the method proposed by C. Kircher (Kircher 1993) which considers PGV of each ground motion as a physical characteristic in calculation of its scale factor. Using this method, the scale factors are presented in Table 3.

Table 3. Scaling factors based on the physical approach.

S_1	S_2	S_3	S_4	S_5	S_6	S_7
1.46	1.39	1.35	1.12	1.13	0.88	1.63

Fig. 3 shows three average spectrums corresponding to each method of scaling. It can be noted that in the range of periods near 1.3 s which is the fundamental period of our structure, the uniform scaling spectrum stands over the others.

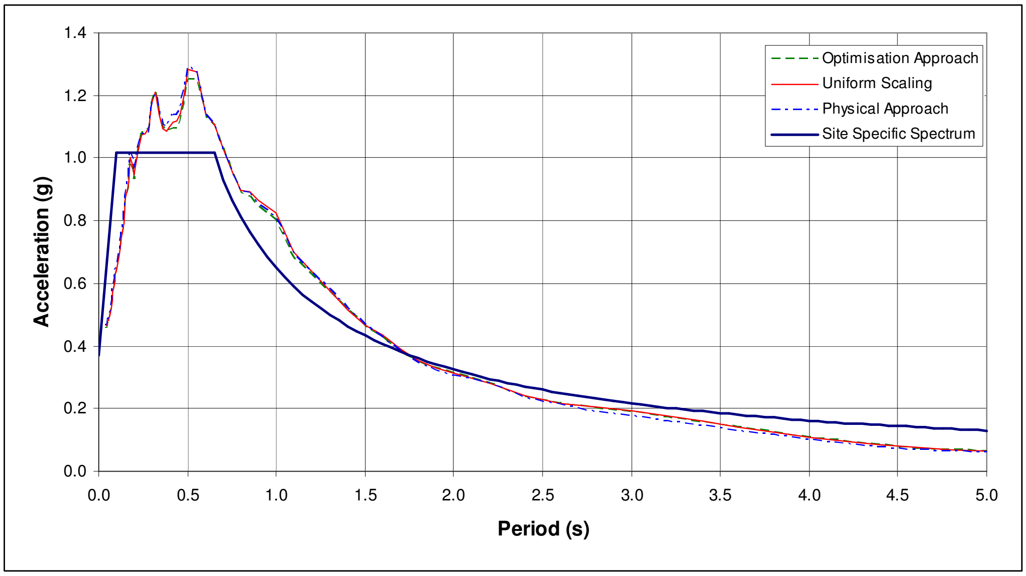

Figure 3. Comparison of different average spectra with site specific spectrum

Presentation of Results

Among the outputs of analysis, here we present the average of the shear deformation of main wall panels and drift of the main walls. For the shear deformations, the contours of usage ratios are presented for the most critical wall (Wall C). For the drift of main walls, the profile of drift is presented for all stories.

Shear Deformations of Main Wall Panels

Shear deformations of the panels are presented in terms of Usage Ratio which is the ratio of maximum shear deformation of the panel to its acceptable value according to FEMA 356. Fig. 4 shows the contours of usage ratios for panels of the most critical wall (Wall C) and for three methods of scaling. The average of seven pairs is presented.

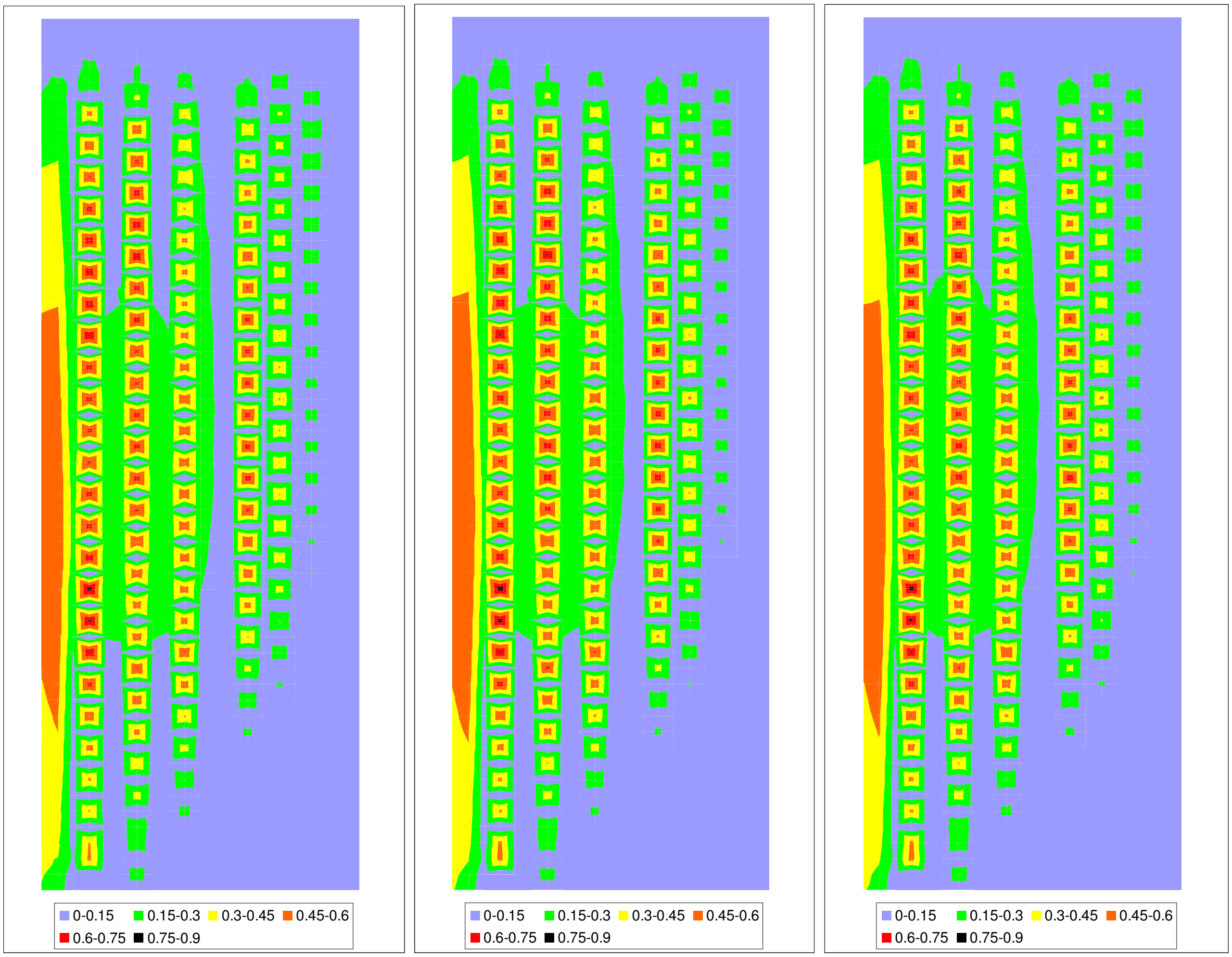

Figure 4. The average of shear deformation of panels, method of Kircher (left), uniform scaling method (center), method of Naeim and Bhatia (right)

The maximum usage ratios are presented in Table 4 for three walls and three methods. The maximums correspond to uniform scaling method but not significantly.

Table 4. Maximum usage ratios of shear wall panels

	Physical	**Uniform**	**Optimization**
Wall A	0.694	0.721	0.689
Wall B	0.531	0.518	0.516
Wall C	0.830	0.855	0.835

Drift of the Structure

Fig. 5 shows the distribution of drift of the three shear walls for the three methods of scaling. The average of seven pairs is presented.

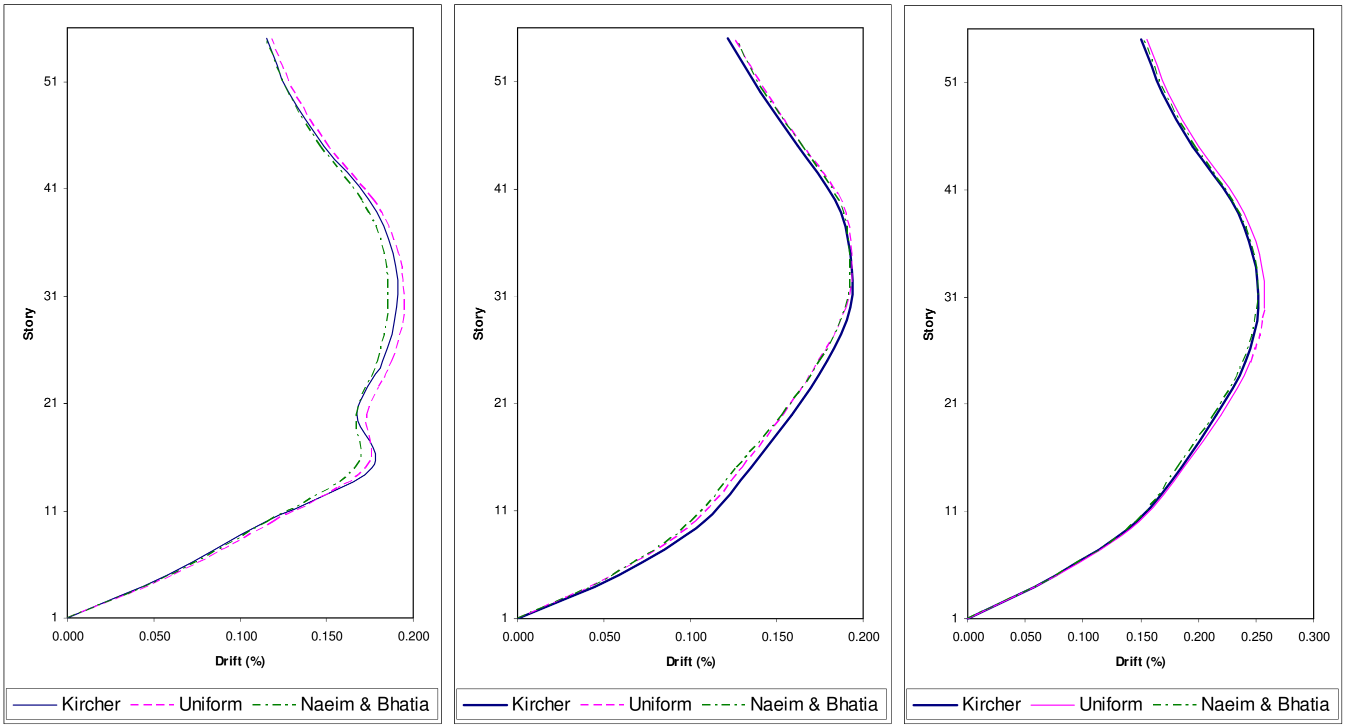

Figure 5. Average of drift of shear walls, main wall A (left), main wall B (center), main wall C (right).

Maximum drifts are presented in Table 5. Maximums correspond to the uniform scaling method but not significantly.

Table 5. Maximum drifts of shear walls.

	Physical	Uniform	Optimization
Wall A	0.191	0.195	0.186
Wall B	0.192	0.194	0.193
Wall C	0.252	0.257	0.251

Conclusions

Despite the fact that scale factors calculated using three different methods are significantly different, the results are very similar (almost identical). The more records we use, the more coincidence with the site specific spectrum is attainable and seven ground motions are many enough to minimize the dependency of the results on the method of scaling.

Also, irrespective of the similarity of results, the uniform scaling method increases the demand on the structure and causes greater responses. In fact, when the number of records is enough (seven in this case), the uniform scaling method seems to be easier to conduct and more conservative to deduct. It proposes the same scale factor for all of the records, then it does not change the contribution of the ground motion records which have all been recognized equally appropriate (hazard analysis), then it may be considered as the most appropriate method for seven pairs of ground motion records.

In the case of using a fewer number of records, it is expected that different methods produce more dissimilar results. Then, if the site specific spectrum is still considered as a comprehensive measure of the demand of a real earthquake, the optimization approach leads to the more coincident average spectrum. But it should be mentioned that the scale factors should not be so different that they change the concept behind selection of each record when all of the records have been recognized to be equally appropriate to represent the site; for example $0.5<\mathbf{S_i}<1.5$ (Alimoradi et al. 2004).

Acknowledgements

The International Construction Development Co. (I.C.D. Co), Iran, has completely funded the project of evaluation and rehabilitation of the Tehran Tower.

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Appendix 1: Optimization Approach (Naeim, Bhatia 2000)

Definitions

$\mathbf{n}$	Number of pairs of time histories to be averaged.
$\mathbf{f_i(t)}$	5% damped spectrum of the SRSS of any pair of time histories, where $\mathbf{i} < \mathbf{n}$.
$\mathbf{f_D(t)}$	5% damped spectrum of the design-basis earthquake.
$\mathbf{S_i}$	Scale factor used for any pair of time histories, where $\mathbf{i} < \mathbf{n}$ and $\mathbf{S_i} > 0$.
$\mathbf{m}$	Code specified numerical multiplier for the design-basis spectrum.
$\mathbf{T}$	Fundamental period of the structure.
τ	Tolerance, a starting tolerance may be specified by the user, but will be automatically increased if no solution is attained within that tolerance.
α, β	Numeric constants specified by code (here 0.2 and 1.5 respectively).

Calculation Steps

The objective function to be minimized is

$$\mathbf{Z} = \sum_{k=1}^{n}\sum_{i=1}^{n}(\mathbf{S_i} - \mathbf{S_k})^2$$

The constraints are

$$\frac{\sum_{i=1}^{n} S_i f_i(t_1)}{n} > m f_D(t_1)$$

$$\frac{\sum_{i=1}^{n} S_i f_i(t_1)}{n} < \tau m f_D(t_1) \qquad \alpha T < t_1 < \beta T$$

The trivial optimal solution is $S_1 = S_2 = S_3 = \ldots = S_7$ and this should be the starting solution vector. The problem is therefore not linear.

Appendix 2: Physical Approach (Kircher 1996)

Definitions of Input Data

n	Number of pairs of horizontal time history components.
PGV_{ji}	Peak ground velocity, **PGV**, of time history, TH_{ji}.
RS_{ji}	Response spectrum (5%-damping) of time history, TH_{ji}.
TH_{ji}	Time history of the **i**th pair in the **j**th horizontal direction (i.e., **j** = 1 or 2).
TRS	Target response spectrum (here defined as 1.4 times the site specific spectrum).
T_{eff}	Effective period of structure in seconds at intersection of capacity/demand curves.

Definitions of Calculated Data

ARS	Response spectrum shape of time histories taken as the mean of composite response spectra, CRS_i, normalized by composite peak ground velocity, $CPGV_i$.
$CPGV_i$	Composite peak ground velocity of the **i**th horizontal time history pair.
CRS_i	Composite response spectrum of the **i**th horizontal time history pair.
TH_{ji}	Time history of the **i**th pair in the **j**th horizontal direction (i.e., **j** = 1 or 2).
M_{ARS}	Response spectrum multiplier used to fit the response spectrum shape, **ARS**, to the target response spectrum, **TRS**.
STH_{ji}	Scaled time history of the **i**th pair in the **j**th horizontal direction.

Calculation Steps

For near-source records, rotate each pair of horizontal components to fault normal and fault parallel directions (note: rotation affects all parameters, including time histories, TH_{ij}, response spectra, RS_{ij}, and peak ground velocity, PGV_{ij}).

For each pair of earthquake components, calculate the composite spectrum, CRS_i, and the composite peak ground velocity, $CPGV_i$.

$$CRS_i = (RS_{1i}^2 + RS_{2i}^2)^{1/2}$$
$$CPGV_i = (PGV_{1i}^2 + PGV_{2i}^2)^{1/2}$$

Find the average value of composite spectra normalized by composite peak ground velocity.

$$ARS = \frac{1}{n}\sum \frac{CRS_i}{CPGV_i}$$

Determine the response spectrum multiplier, M_{ARS}, that is required to increase (or decrease) the response spectrum shape, **ARS**, such that it matches the target response spectrum, **TRS**, at the period(s) of interest.

$$M_{ARS} \approx TRS/ARS$$
$$(ARS \propto 1/T \text{ at } T_{eff} \geq 1 \text{ second})$$

For each pair of earthquake time histories, scale both horizontal components by the ratio of the response spectrum multiplier to the composite peak ground velocity.

$$\mathbf{STH_{1i} = (M_{ARS}/CPGV_i)TH_{1i}}$$
$$\mathbf{STH_{2i} = (M_{ARS}/CPGV_i)TH_{2i}}$$