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# DUAL VS. AMPLITUDE SCALING IN NONLINEAR TIME-HISTORY ANALYSIS

J.E. Martinez-Rueda[1] and F. Hamedi[2]

## ABSTRACT

Modern design codes, such as the ASCE/SEI7 or the Eurocode, allow the use of a family of scaled natural accelerograms to define the seismic input needed for the estimation of inelastic structural response. In view of this, a number of selection and scaling criteria have been proposed over the years. When it comes to scaling, the traditional approach has been to think in terms of scaling the amplitude of the accelerograms to match the intensity of the seismic input with that associated with the design spectrum. Less attention has been devoted to dual scaling (*i.e.* a combination of time and amplitude scaling). When it comes to the intensity to match, it is now clear that the matching of spectral acceleration does not appear to be the one and only best option for all possible combinations of the fundamental seismic parameters of the structure under analysis, *i.e.* fundamental period and inelastic strength.

This work presents a comparative study where ductility demands of inelastic structures (idealized as SDOF systems) are estimated by time-history analysis using families of natural accelerograms scaled by different criteria. The first type of scaling criteria deals with amplitude scaling guided by either spectral acceleration or spectrum intensity; therefore no modification of the frequency content of the seismic input is imposed. The second type of scaling criteria deals with dual scaling with the view of minimizing the geometrical differences between the response and the design spectra with the option of accounting for the period and inelastic strength of the structure under analysis. It is concluded that dual scaling offers an interesting and yet simple approach to make an effective and more flexible use of natural accelerograms in engineering practice.

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# Dual vs. Amplitude Scaling in Nonlinear Time-history Analysis

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## ABSTRACT

This work presents a comparative study where ductility demands of inelastic structures are estimated by time-history analysis using families of natural accelerograms scaled by different criteria. The first type of scaling criteria deals with amplitude scaling guided by either spectral acceleration or spectrum intensity; therefore no modification of the frequency content of the seismic input is imposed. The second type of scaling criteria includes methods relying on dual scaling with the view of minimising the geometrical differences between the response and the design spectra with the option of accounting for the period and inelastic strength of the structure under analysis. It is concluded that dual scaling offers an interesting and yet simple approach to make an effective and more flexible use of natural accelerograms in engineering practice.

## Introduction

It is now generally accepted that reliable estimates of the inelastic demands of earthquake resistant structures can be obtained by nonlinear inelastic time-history analysis. The specification of the earthquake ground motion (EGM) for this type of analysis is still an open question in earthquake engineering research. One popular option is to use natural accelerograms which must be selected and scaled to match as close as possible all the seismological parameters affecting the target design spectrum, including the geology of the site, distance to seismic source and even the type of faulting. Further refinements for EGM scaling criteria account for the period of the structure under analysis [1,2] or even a combination of both the period and the inelastic strength of the structure [3].

Normally EGM motion scaling adopts as main criterion of scaling the matching of the spectral acceleration of the fundamental period of the structure under analysis. A recent study [4] comparing different approaches to set the intensity to match in EGM scaling confirms that there is not a unique ground motion parameter (GMP) of best association with displacement ductility demand $\mu_\Delta$ over a wide range of structural parameters including the fundamental period assessed at yield condition $T_y$ (also denoted as initial period) and the inelastic strength of the structure assessed by the yield coefficient $C_y$ (defined as the ratio between the lateral strength at yield condition and the total weight of the structure). This is exemplified in Figure 1, where for the family of structures under study (with strength $C_y$ = 0.2) it is clear that Housner Intensity $SI_H$ is the most stable GMP for scaling as it normally shows a consistent higher value of the coefficient

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of determination $R^2$ of the $SI_H$ *vs.* $\mu_\Delta$ relationship for a wide range of periods $T_y$. However, this figure also reveals that for very short period structures ($T_y \leq 0.1$ sec) peak ground acceleration *PGA* provides a slightly more reliable option for scaling when compared to $SI_H$. On the other hand, for structures with $T_y \geq 1.0$ sec, the spectral acceleration of the structure under analysis $SA(T_y)$ seems to be a slightly better option than $SI_H$ for EGM scaling.

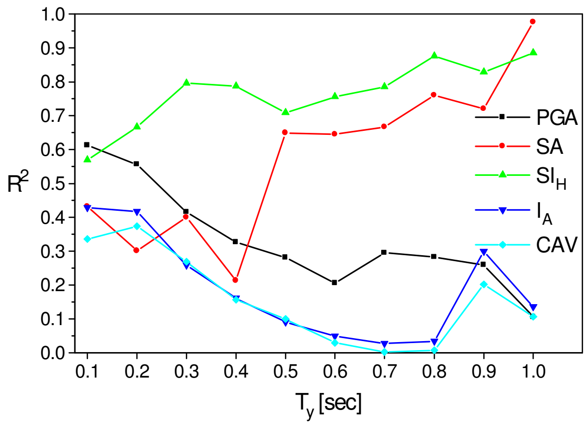



Figure 1. Comparison of GMPs performance for a family of inelastic structures with $T_y$ between 0.1 and 2.0 sec and with $C_y = 0.2$ [3].

Other ways of modifying the intensity of EGM consist of applying time-scaling or a combination of time-scaling and amplitude-scaling referred here as *dual scaling*. These two options modify the frequency content of the EGM and hence the shape of the response spectrum. A recent study on dual scaling [5] confirms that dual scaling offers an attractive tool to modify natural accelerograms to improve the fitting between the response spectrum of the scaled accelerogram and the target spectrum to 'match'.

**Objectives and scope**

The main objective of this paper is to compare the displacement ductility demands estimated when using simple amplitude and dual scaling criteria. To that effect, three structures idealized as inelastic SDOF systems and representative of the main branches of a typical target design spectrum are analyzed under the action of scaled natural accelerograms recorded on rock. Results are assessed in terms of the goodness of fit between the mean response spectrum and the target spectrum, as well as, the stability of the shape of the mean response spectrum as affected by the period $T_y$ of the structure under analysis.

**Study on estimated $\mu_\Delta$ and goodness of fit of the mean response spectrum**

This study considers a hypothetical case when the number of available EGMs recorded at the site of interest is not extensive. Hence earthquake records from other regions of the world have to be imported to define the seismic input. However, the seismic faulting affecting the site is assumed to be known; hence selected EGMs match the faulting mechanism.

**Site Conditions and Selected Earthquake Ground Motion**

The site of interest is assumed to be rock and the main source of EGM is assumed to be a normal fault. The target design spectrum is the so-called horizontal elastic *response spectrum* of EC8 [2] for ground Type A and spectral shape Type 1 for 5% damping. The spectrum was anchored to a $PGA$ = 3 m/sec$^2$ and the regions of the spectrum were delimited using the standard values recommended by the code.

A data set of 132 natural accelerograms of horizontal excitation identified in [6] as being generated by normal faulting and recorded on rock is considered as the available EGM. From this data set 7 accelerograms were initially chosen. The selection was guided by the best goodness of fit between the design and the response spectra of the EGM, both normalized with respect to $PGA$. The goodness of fit was assessed by $\varepsilon^2$ defined by:

$$\varepsilon^2 = \sum [PSA_d(T_y) - PSA_r(T_y)]^2 \tag{1}$$

where $PSA_d(T_y)$ is the pseudoacceleration of the design spectrum at period $T_y$; $PSA_r(T_y)$ is the pseudoacceleration of the response spectrum of the natural accelerogram evaluated at period $T_y$. The period range used in eq. 1 was from 0 to 2.5 sec.

However, as the two horizontal components of an earthquake record are statistically related, when these components of a record were identified between the initial group of 7 EGMs of best fit to the target spectrum, only the one with lower $\varepsilon^2$ was chosen and the other was discarded. The final set of 7 EGM of best fit to the target spectrum are identified in Table 1. A recent study [7] confirms that the use of 7 natural accelerograms results in reliable estimates of ductility demands.

Table 1. Natural accelerograms selected for the study.

| accelerogram Code | $PGA$ [m/sec$^2$] | $M_w$ | $d$ [Km] | Date | Country | Station |
|---|---|---|---|---|---|---|
| 000292xa | 0.574 | 6.9 | 10 | 23/11/1980 | Italy | Auletta |
| 005895xa | 0.129 | 5.2 | 30 | 09/07/1984 | Greece | Veria-Cultural Centre |
| 006100ya | 0.185 | 6.5 | 48 | 13/05/1995 | Greece | Kastoria-OTE Building |
| 000286ya | 0.343 | 6.9 | 60 | 23/11/1980 | Italy | Arienzo |
| 000290xa | 2.145 | 6.9 | 14 | 23/11/1980 | Italy | Sturno |
| 000369xa | 0.340 | 5.9 | 44 | 07/05/1984 | Italy | Roccamonfina |
| 000382ya | 0.148 | 5.5 | 13 | 11/05/1984 | Italy | Atina |

**Structures under Study**.

The mean ductility demands $\mu_\Delta$ of three structures (one representative of each of the main branches of the design spectrum) were assessed by nonlinear inelastic time-history analysis using the selected EGM scaled by different criteria. The structures selected for the study had initial periods $T_y = 0.1$, 0.3 & 1.0 sec, damping ratio of 5% and strength characterized by a yield seismic coefficient $C_y = 0.25$. The hysteresis of the structure was modeled with a bilinear model with kinematic hardening and a post-yield stiffness of 2% of the initial stiffness defining $T_y$.

## Scaling Criteria

Initially, three primary scaling criteria for the seismic input were selected, namely:

- Amplitude scaling by spectral acceleration *SA* at $T_y$
- Amplitude scaling by spectrum intensity *SI*
- Dual scaling (amplitude scaling to match *SI* + time scaling to match the amplification band $T_{amp}$)

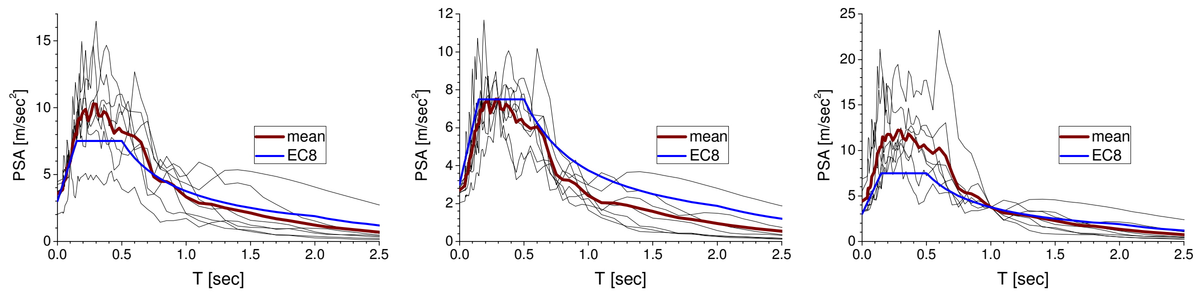
The amplification band $T_{amp}$ is defined as the period at which the acceleration in the descending branch of the design spectrum is equal to *PGA*; in other words $T_{amp}$ is the length of the period interval where *SA* is greater than or equal to *PGA*.

ASCE/SEI-7 [1] does not allow the mean response spectrum of the family of scaled accelerograms to be below the design spectrum over the period range $0.2T_y$ to $1.5T_y$. To assess the consequences of applying this additional constraint, three 'hybrid' scaling criteria were also considered. These consisted of scaling further the EGM defined by the primary criteria to comply with the ASCE/SEI-7 constraint and are referred here as:

- *SA* scaling + ASCE/SEI-7 correction
- *SI* scaling + ASCE/SEI-7 correction
- Dual scaling + ASCE/SEI-7 correction

## Results

Figures 2 to 4 compare the family of scaled response spectra using the primary scaling criteria , both with the mean response spectrum and with the design spectrum.

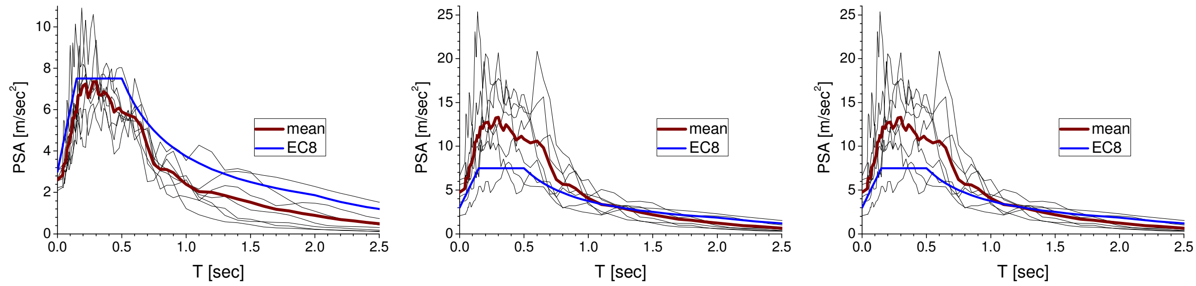



(a) $T_y = 0.1$ sec (b) $T_y = 0.3$ sec (c) $T_y = 1.0$ sec

Figure 2. Family of response spectra of EGM scaled by spectral acceleration for structures of different initial periods.

As expected, when the records are scaled by $SA(T_y)$ the three plots of Figure 2 show a perfect match between the mean response spectrum and the design spectrum exactly at the three values of $T_y$ considered in the study. It is observed that this scaling criterion leads to significantly different mean response spectra depending on the structure under analysis.

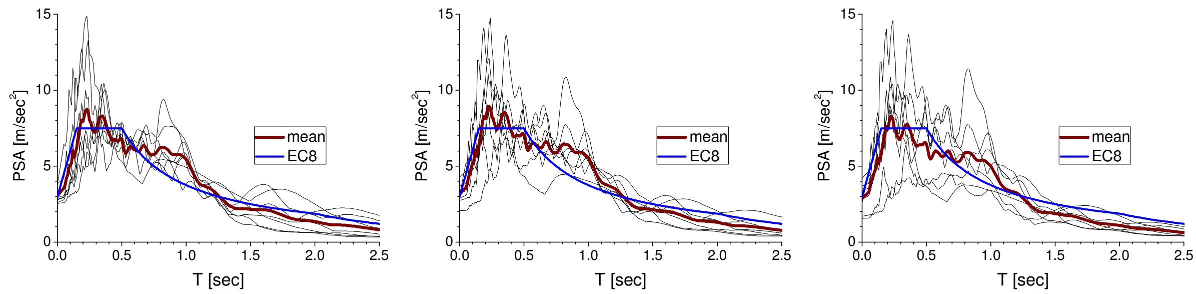
When the records are scaled using a system of spectrum intensity scales [3] (described in the appendix), Figure 3 indicates that for the short period structure ($T_y$ =0.1 sec) this scaling criterion leads to a general deficit of spectral acceleration as the mean response spectrum consistently lies under the target design spectrum. This anomalous performance of the scaling criterion may be due to the fact that the system of spectrum scales was calibrated for values of the postyield stiffness ratio $\alpha$ in excess of 0.05 and the inelastic response of short period structures with bilinear response is very sensitive to the postyield stiffness.




(a) $T_y = 0.1$ sec (b) $T_y = 0.3$ sec (c) $T_y = 1.0$ sec

Figure 3. Family of response spectra of EGM scaled by spectrum intensity.

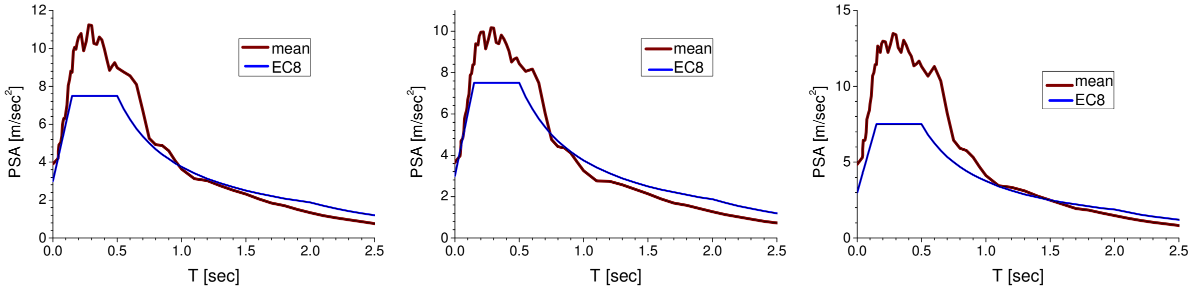
Figure 4 reveals that when dual scaling is adopted, both the mean response spectrum shape and the order of magnitude of its ordinates are less sensitive to the period $T_y$ of the structure under analysis. It is also important to note that, in comparison with Figures 2 and 3, the goodness of fit of the mean response spectrum is largely improved. These findings suggest that dual scaling provides more stable results when compared with amplitude scaling.




(a) $T_y = 0.1$ sec (b) $T_y = 0.3$ sec (c) $T_y = 1.0$ sec

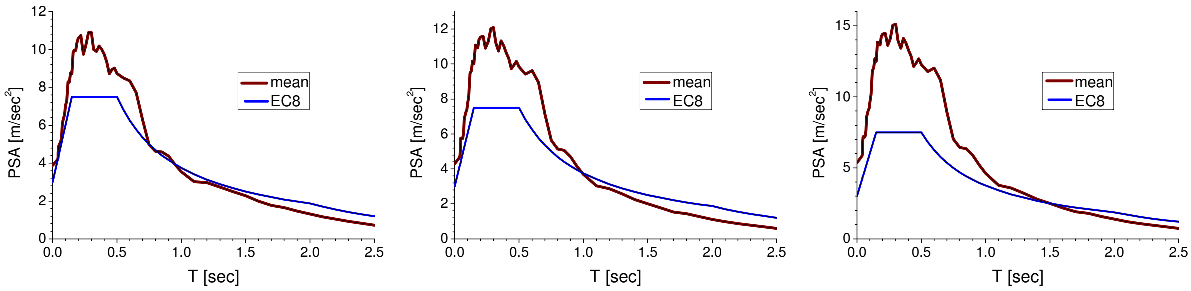
Figure 4. Family of response spectra of EGM subjected to dual scaling

Figures 5 to 7 compare the mean response spectra with the target spectrum when the primary scaling criteria are modified to account for the ASCE/SEI-7 constraint. In all cases, excessive ordinates of the mean spectra and reduced goodness of fit are observed, particularly for amplitude scaling (by *SA* or by *SI*).



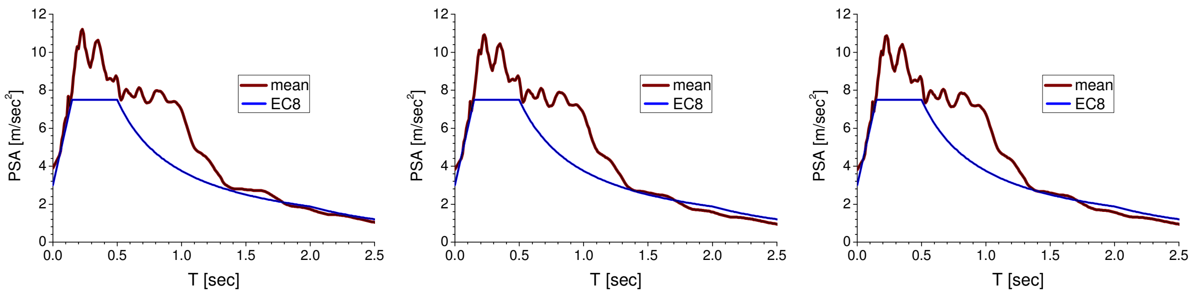

(a) $T_y = 0.1$ sec (b) $T_y = 0.3$ sec (c) $T_y = 1.0$ sec

Figure 5. Mean response spectra of EGM scaled initially by spectral acceleration and with further scaling to comply with the ASCE/SEI-7 constraint.




(a) $T_y = 0.1$ sec (b) $T_y = 0.3$ sec (c) $T_y = 1.0$ sec

Figure 6. Mean response spectra of EGM scaled initially by spectrum intensity and with further scaling to comply with the with the ASCE/SEI-7 constraint.




(a) $T_y = 0.1$ sec (b) $T_y = 0.3$ sec (c) $T_y = 1.0$ sec

Figure 7. Mean response spectra of EGM subjected initially to dual scaling and with further scaling to comply with the ASCE/SEI-7 constraint.

Finally, Figure 8 shows a comparison of mean ductility demands $\mu_\Delta$ obtained by nonlinear inelastic time-history analysis for the three structures under the action of the scaled EGM according to the six scaling criteria under study. It is evident that as $T_y$ increases, the scatter of predicted mean ductility demands for different scaling criteria is significantly reduced. In fact, for practical purposes, for the 'long' period structure ($T_y$ = 1.0 sec) the six scaling criteria can be assumed as converging into a common point. This is somehow expected as the variability of spectral ordinates is normally period dependent and with higher variability normally observed at shorter periods. The further scaling required to comply with the ASCE/SEI-7 constraint resulted in large increases of mean ductility demands both for amplitude and dual scaling criteria. These demands appear to be overconservative when one is aware of the big differences and poorer fit between the target design spectrum and the mean response spectra observed in Figures 5 to 7.

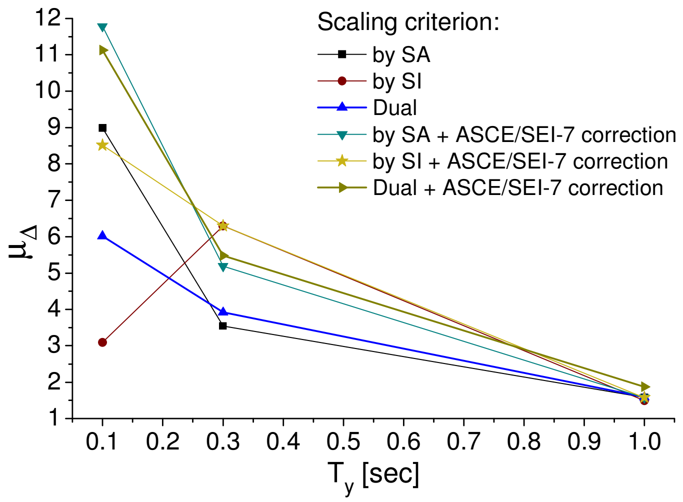



Figure 8. Comparison of predicted mean ductility demands obtained by scaling the EGM according to different scaling criteria.

## Conclusions

This paper has compared a number of amplitude *vs*. dual criteria for the scaling of EGM in terms of their ability to lead to stable mean spectra shapes and realistic ductility demands. Three primary criteria based on amplitude scaling by spectral acceleration, on amplitude scaling by spectrum intensity, and on dual scaling (amplitude + time scaling) were first considered.
The scaling factors of the primary criteria were then further amplified to comply with the ASCE/SEI-7 constraint to avoid that the mean response spectrum was located beneath the target spectrum over the period interval $0.2T_y$ to $1.5T_y$.

In terms of the stability of the goodness of fit observed between the mean response spectrum and the design spectrum for different periods of the structure under analysis, it is concluded that the use of dual scaling offers an attractive tool to obtain sensible estimates of ductility demands by nonlinear inelastic time-history analysis.

For the structures and the EGMs considered in this paper, the correction of the scaling factors of the primary scaling criteria to comply with the ASCE/SEI-7 constraint lead to poorer fit between the mean response spectrum and the target spectrum. However, one should be mindful that other methods and algorithms (not considered in this paper) for selecting the family of EGMs before their scaling, might counteract the negative effect of the ASCE/SEI-7 constraint.

## Appendix

Table 1. System of Spectrum Intensity scales for amplitude scaling [3].

| $\alpha$ | $C_y$ | $T_y \le 0.60$ sec | $0.60 < T_y \le 1.60$ | $T_y > 1.6$ sec |
|---|---|---|---|---|
| | $C_y \le 0.10$ | $SI_H$ | $SI_{yh}$ | $SI_{yh}$ |
| $\alpha \le 0.10$ | $0.10 < C_y \le 0.30$ | $SI_{yh}$ | $SI_H$ | $SI_M$ |
| | $C_y > 0.30$ | $SI_M$ | $SI_H$ | $SI_M$ |
| | $C_y \le 0.10$ | $SI_{yh}$ | $SI_{yh}$ | $SI_{yh}$ |
| $0.10 < \alpha \le 0.30$ | $0.10 < C_y \le 0.30$ | $SI_{yh}$ | $SI_H$ | $SI_M$ |
| | $C_y > 0.30$ | $SI_{yh}$ | $SI_H$ | $SI_M$ |
| | $C_y \le 0.10$ | $SI_M$ | $SI_M$ | $SI_M$ |
| $\alpha > 0.30$ | $0.10 < C_y \le 0.30$ | $SI_M$ | $SI_{yh}$ | $SI_{yh}$ |
| | $C_y > 0.30$ | $SI_{yh}$ | $SI_{yh}$ | $SI_{yh}$ |

$$SI_H = \frac{1}{2.4}\int_{0.1}^{2.5} PSV(T,\xi)\,dT \text{ = Housner spectrum intensity}$$

$$SI_M = \frac{1}{2.4}\int_{T_y}^{2T_y} PSV(T,\xi)\,dT \text{ = Spectrum intensity according to Matsumura's criterion}$$

$$SI_{yh} = \frac{1}{T_h - T_y}\int_{T_y}^{T_h} PSV(T,\xi)\,dT \text{ =Spectrum intensity according to Martinez-Rueda's criterion}$$

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