Evaluating A New Proxy For Spectral Shape To Be Used As An Intensity Measure

Eden Bojorquez[a], Iunio Iervolino[a] and Gaetano Manfredi[a]

[a]*Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli Federico II*
Via Claudio 21, 80125, Naples, Italy, Tel: +390817683672

Abstract. The possibility to use a new vector-valued ground motion intensity measure (IM) is analyzed; it is based on the spectral acceleration at first mode (*Sa*) and a parameter proxy for the spectral shape, namely N_p. The potential of the vector $<Sa, N_p>$ is explored by efficiency comparison with other IMs. It will be illustrated how the form of the vector $<Sa, N_p>$ may represent an improvement in predicting the seismic response in terms of ductility, dissipated hysteretic energy and Park and Ang damage index for nonlinear single degree of freedom (SDOF) structures subjected to ordinary, narrow-band and near-source pulse-like records.

Keywords: Intensity measures, scalar intensity measures, probabilistic seismic demand analysis, dissipated hysteretic energy, Park and Ang damage index, ductility displacement demand.

INTRODUCTION

Due to all the uncertainties associated with the response of structures subjected to earthquakes, it is required a probabilistic approach. Probabilistic seismic demand analysis (PSDA) is used as a tool to estimate the reliability of structures subjected to earthquakes, through the evaluation of the mean annual frequency (MAF) of exceeding a specified value of an earthquake demand parameter (EDP) using the next equation:

$$\lambda_{EDP}(x) = \int_{IM}\int_{M}\int_{R} P[EDP > x \mid IM, M, R] f(IM \mid M, R) f(M, R)\, dr\, dm\, d(im) \qquad (1)$$

where $\lambda_{EDP}(x)$ is the MAF of EDP exceeding a value x, $f(IM \mid M,R)$ is the conditional distribution function of IM given magnitude (*M*) and distance (*R*), (e.g. an attenuation law). $f(M,R)$ is the joint probability density function of *M* and *R*. Finally, $P[EDP > x \mid IM, M, R]$ is the failure probability of the structure as a function of IM, *M* and *R*. If $P[EDP > x \mid IM, M, R] = P[EDP > x \mid IM]$ then the IM is said *sufficient* [1, 2] since its ability to predict the structural response is independent of *M* and *R* given IM. An IM that shows good correlation with the structural response (e.g. small variability of EDP given IM) is said to be *efficient* [2]. A well chosen IM is important for the next reasons: 1) it can be used to joint the relation between seismologist and earthquake engineering, by decoupling the ground motion hazard and nonlinear dynamic analysis as suggested by Cornell and co-workers [1-3]; 2) it can avoid the need of a detailed

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ground motion record selection, and reduce the number of records used for computational analysis involved in PSDA [4]. In 1952, Housner [5] proposed to use the area under the velocity spectrum as an IM; twenty tears later Von Thun et al [6] suggested the area under the acceleration spectrum in a range of period 0.1 to 0.5 to analyze dams. In the last years, the spectral acceleration at first mode ($Sa(T_1)$, here named also *Sa*) became very popular, but due to its insufficiency in some cases [7] as predictor of EDPs; recently, other advanced both scalar and vector-valued IMs have been proposed. In particular, the vector $<Sa, \varepsilon>$ has resulted sufficient; efficient in many cases [7], but Tothong and Luco [8] showed its ineffectiveness to predict the response of structures subjected to pulse-like records, and they proposed an advanced scalar IM based on the inelastic spectral displacement. It results efficient for ordinary and pulse-like records, at least to predict interstory drifts; however, the application of this IM is more complicated. Another vectorial IM $<Sa, R_{T1,T2}>$ (based on the originally scalar proposed by Cordova et al [9], where $R_{T1,T2}$ is the ratio between the spectral acceleration at period T_2 divided by spectral acceleration at period T_1), has resulted effective for pulse-like records [10]. Baker and Cornell [11] also explored how to avoid peaks or valleys using the geometrical mean of spectral acceleration in a range of periods, $Sa_{avg}(T_1 ... T_N)$. It can be observed in all the IMs mentioned one important aspect: the efforts trying to propose different alternative IMs in many cases are concentrated in general on spectral shape, because its importance as a predictor of structural response [1-11]. (However, it is important to say that similar values of $<Sa, R_{T1,T2}>$, $<Sa, \varepsilon>$ and $Sa_{avg}(T_1 ... T_N)$ in some cases provoke different spectral shapes, and with this important differences in the response).

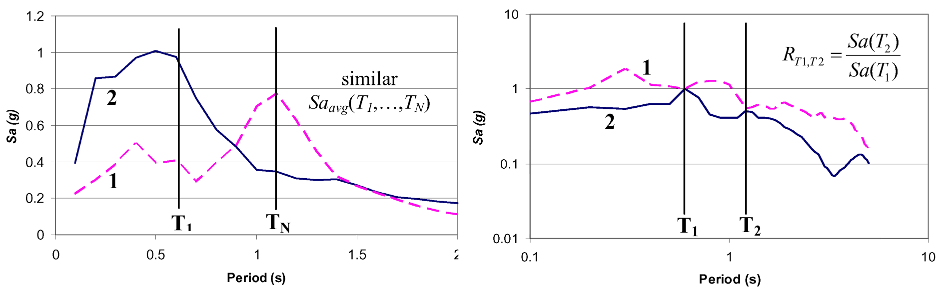
The motivation of this paper is to analyze a new vector-valued IM based on *Sa* and a parameter named N_p, for two reason: a) it is consistent with the spectral shape, and 2) the vector $<Sa, N_p>$ could be a good candidate to predict EDPs related not only with maximum also with energy demands (due to the importance for long duration ground motions or structures with low cyclic capacity [12-15]).

SEISMIC RECORDS

To the aim of the present paper, three sets of seismic records were considered to represent ordinary, near-source pulse-like and narrow-band motions. The set of ordinary 194 records used in a previous study [16, Table A.3; except Chi-Chi Taiwan] has closest distance to rupture between 15 and 95kms, and magnitudes from 5.65 to 7.90. The pulse-like records consist in a set of 48 motions with a pulse period close to 1s (mean $Tp \approx 1.0$s). The records were rotated in the fault-normal direction. The earthquake magnitude range is from 5.6 to 7.6, and the closest distance to rupture less than 22kms. The pulse-like set is a subset of that in [17]. The ordinary and pulse-like records correspond to firm soil or rock. Due to narrow-band motions demand large energy amount to the structures compared to broad-band motions [14], they were also considered for the purposes of this study. A set of 31 ground motion records obtained from the soft-soil of the Valley of Mexico were used. The magnitude range is from 6.9 to 8.1 (including the 1985 Mexican Earthquake). The records previously used by [15] were selected for a soil period close to 2 seconds and correspond to far field.

A NEW PROXY FOR SPECTRAL SHAPE TO BE USED AS AN IM

It has been mentioned that IMs in some cases can not represent with good accuracy the spectral shape. To clarify this, figure 1a shows two response spectra with similar values of $Sa_{avg}(T_1 \ldots T_N)$, it is clear how the spectral shape of both records is completely different, which suggests that different responses will be obtained. Figure 1b illustrates the same case scaling to similar *Sa* and $R_{T1,T2}$, and it is because the path of the structure since its elastic behavior until its arrives to the maximum nonlinear behavior is not considered. In other words, there is no information about the spectral shape for periods larger than T_2 and smaller than T_1. The idea of Housner and Von Thun to use the area under the acceleration spectrum in a range T_1-T_N (figure 2) could be a good candidate to know the spectral shape, because it considers the path since the structure has a period T_1 until it finishes with an elongated period of T_N, but to be consistent with the spectral shape, it is better to express the spectral area normalizing by $Sa(T_1)$ and T_1 to account for the position of the structure in the spectrum, and it lets introduce a new parameter named N_p (Eq. 2), which may give that in the most of the cases, similar values of this parameter provoke similar spectral shapes. It is also possible to approximate N_p as a function of geometrical mean of spectral acceleration in a range of periods interest (Eq. 2).



a) b)

FIGURE 1. Elastic response spectra for two records a) scaled for the same geometrical mean $Sa_{avg}(T_1,\ldots,T_N)$ that reflects different spectral shapes; b) scaled for same values of *Sa* and $R_{T1,T2}$ that also reflects different spectral shapes.

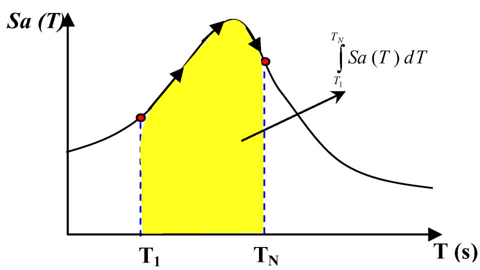


FIGURE 2. Example of an elastic response spectrum and the use of the area under the curve to characterize spectral shape.

$$N_p = \frac{1}{T_1\, Sa(T_1)} \int_{T_1}^{T_N} Sa(T)\, dT \approx \frac{Sa_{avg}(T_1 .. T_N) * (T_N - T_1)}{T_1\, Sa(T_1)} \tag{2}$$

The term N_p in Eq. 3 was adopted, because it represents the contribution of N points of the spectrum. The normalizing between $Sa(T_1)$ let N_p be independent of the scaling level of the records based on $Sa(T_1)$.

EFFICIENCY OF DIFFERENT VECTOR-VALUES INTENSITY MEASURES

In this part, the efficiency of the vectors $<Sa, \varepsilon>$, $<Sa, R_{T1,T2}>$ and $<Sa, N_p>$ as predictors of the structural response is compared through the analyses of nonlinear SDOF. Three EDPs were studied. The first EDP considered here is the ductility displacement demand μ_D (ratio of maximum displacement D_m and yielding displacement D_y). The second is D_{hyst} (parameter based on normalized dissipated hysteretic energy by displacement and strength yielding F_y) that captures information about the ground motion duration effects or cumulative demands [18]. D_{hyst} is defined in Eq. 3.

$$D_{hyst} = 1 + \frac{E_H}{F_y\, D_y} \tag{3}$$

Finally, the last EDP considered is the well known Park and Ang damage index (I_{DPA}) [19] for all the experimental evidence existing behind this parameter. The expression of I_{DPA} is illustrated in Eq. 4, in this equation μ is the ductility capacity, and β is a parameter that represents the contribution of dissipated hysteretic energy to the damage, a value of β=0.15 was used [20].

$$I_{DPA} = \frac{\mu_D}{\mu} + \beta \frac{E_H}{F_y\, D_y\, \mu} \tag{4}$$

Analyses for ordinary records

A SDOF with T=0.6s bilinear behavior, 5% of postyielding stiffness and 5% of critical damping was analyzed. First, the records were scaled for similar values of $S_a(T_1)$ equals to 1g, and then the relation between the second parameter of the vector and the different EDPs was obtained. Figure 3 shows the relation between ε (where epsilon was computed using the Boore and Atkinson [21] attenuation law), $R_{T1,T2}$ and N_p with the displacement ductility demand. Figure 4 illustrates the results for $R_{T1,T2}$ and N_p in respect to I_{DPA}. A good correlation exists with displacement ductility demands and I_{DPA}, especially for $R_{T1,T2}$, and N_p; however, it is clear how the efficiency of N_p compared with $R_{T1,T2}$ is moderately larger. Similar results were obtained for D_{hyst}, they are not included here for the sake of brevity, but the summary is given in table 1. It is observed the less dispersion for the vector $<Sa, N_p>$, and this is valid in the prediction of all the EDPs. For the case of ductility demands and <*Sa*, N_p>, the dispersion is ($\sigma_{ln}(\mu)=0.228$) which is reduced near to 50% compared for a scaling criterion based on *Sa* ($\sigma_{ln}(\mu)=0.40$). This implies a reduction in the number of records required for the analyses. The value of T_2 for $R_{T1,T2}$ results 2 times T_1 (similar to the value proposed by Cordova et al [9]) and T_N for N_p equals to $2.5T_1$, and they correspond to the optimal values obtained from the analyses (the values where the minimum standard deviation occurs). The results suggest that the best candidates are N_p and $R_{T1,T2}$, while ε results in larger dispersion for the EDPs considered.

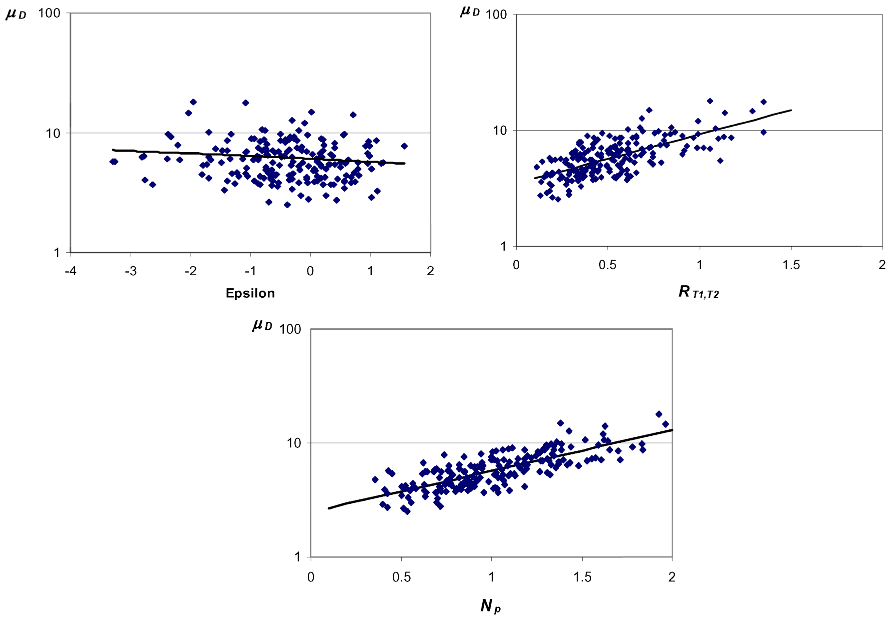


FIGURE 3. Ductility prediction for a SDOF with T=0.6s (*Sa*=1g) for: a) epsilon, b) $R_{T1,T2}$ and c) N_p.

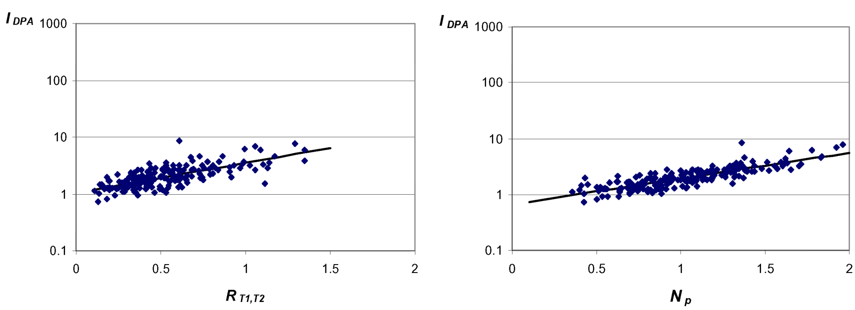


FIGURE 4. I_{DPA} prediction for a SDOF with T=0.6s (*Sa*=1g) for: a) $R_{T1,T2}$ and b) N_p.

TABLE 1. Standard deviations of the natural logarithmic for different IMs (ordinary records, *Sa*=1g).

IM	$\sigma_{ln}(\mu_D)$	$\sigma_{ln}(D_{hyst})$	$\sigma_{ln}(I_{DPA})$
$<Sa, N_p>$	0.228	0.366	0.231
$<Sa, R_{T1,T2}>$	0.260	0.414	0.259
$<Sa, \varepsilon>$	0.365	0.497	0.341

Narrow-Band Motions

For this case, a SDOF with a vibration period of 1s is analyzed. The relation between the different vectorial IMs and the EDPs μ_D and D_{hyst} (except epsilon who shows low correlation with the response) are observed in figures 5 and 6. The higher correlation was observed for the vector based on *Sa* and N_p, and the efficiency of $R_{T1,T2}$ as a predictor of cumulative demands is lower compared with the set of ordinary records. It can be observed in table 2, where the summary of results is illustrated, how the vector here proposed improves in the prediction of the EDPs considered compared with ordinary records. Results also show the improvement on the efficiency with respect to $R_{T1,T2}$, especially for the case of D_{hyst} where the reduction in the dispersion is around 50%. The dispersion of ductility demand in respect to $<Sa, N_p>$ is $\sigma_{ln}(\mu)=0.185$, which is 50% lower than that computed using *Sa* as an IM ($\sigma_{ln}(\mu)=0.378$).

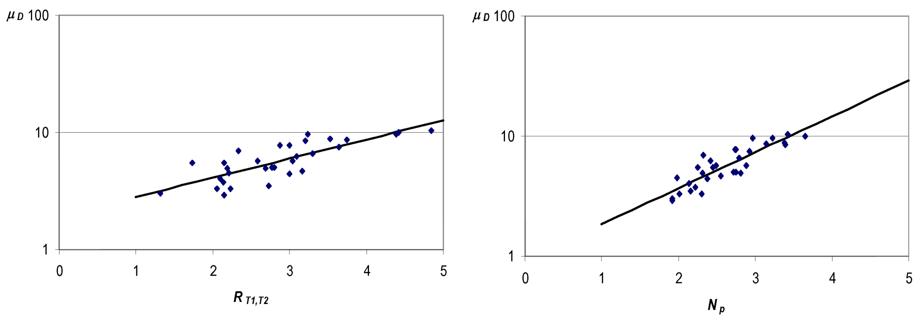


FIGURE 5. μ_D prediction for a SDOF with T=1s (Sa=0.5g) for $R_{T1,T2}$ and N_p.

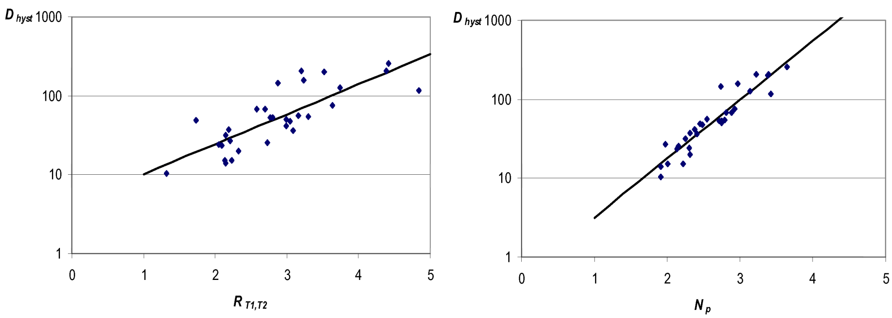


FIGURE 6. D_{hyst} prediction for a SDOF with T=1s (*Sa*=0.5g) for $R_{T1,T2}$ and N_p.

TABLE 2. Standard deviations for different IM (narrow-band motions, *Sa*=0.5g).

IM	$\sigma_{ln}(\mu_D)$	$\sigma_{ln}(D_{hyst})$	$\sigma_{ln}(I_{DPA})$
$<Sa, N_p>$	0.185	0.306	0.235
$<Sa, R_{T1,T2}>$	0.229	0.531	0.375
$<Sa, \varepsilon>$	0.368	0.766	0.585

Near-Source Pulse-like Records

It has been observed that near source pulse-like records have an important influence on structures with a relation T_1/T_p=0.5 [16]. Herein, a SDOF (T_1=0.5s) was subjected to a set of 48 pulse-like records with Tp≈1.0s. For brevity only the summary of the results is given in table 3. In general, the efficiency of $<Sa, N_p>$ to predict EDPs is similar that in the case of narrow-band motions. As [10] suggests for pulse-like records, the vector $<Sa, R_{T1,T2}>$ is more efficient compared with the other sets studied. Nevertheless, as in the other cases, the efficiency of the vector $<Sa, N_p>$ continue been moderately larger compared with the other IMs in the prediction of all the EDPs.

TABLE 3. Standard deviations for the different IMs (near-source pulse-like records, *Sa*=0.9g).

IM	$\sigma_{ln}(\mu_D)$	$\sigma_{ln}(D_{hyst})$	$\sigma_{ln}(I_{DPA})$
$<Sa, N_p>$	0.253	0.224	0.169
$<Sa, R_{T1,T2}>$	0.271	0.255	0.263
$<Sa, \varepsilon>$	0.388	0.482	0.384

CONCLUSIONS

The use of the new vector-valued IM based on $Sa(T_1)$ and a proxy for spectral shape named N_p is explored by efficiency comparison with other IMs. It is observed how the vector $<Sa, N_p>$ show, at least moderately, larger efficiency in respect to the vector $<Sa, R_{T1,T2}>$ to predict displacement and energy demands in nonlinear SDOF subjected to ordinary records and pulse-like records. In general, the vectors $<Sa, N_p>$ and $<Sa, R_{T1,T2}>$ result better predictors compared with $<Sa, \varepsilon>$ for all the record sets considered. When the SDOF were subjected to narrow-band motions, the vector $<Sa, N_p>$ showed larger efficiency in respect to ordinary records and to the other IMs analyzed. For narrow-band motions, the efficiency of the vector $<Sa, R_{T1,T2}>$ to predict EDPs that account for energy demands is reduced in respect to the other record sets considered, while $<Sa, N_p>$ shows still a good correlation.
The results in general suggest that the vector $<Sa, N_p>$ seems to be a promising candidate to be an IM useful for predicting displacements and cumulative damage EDPs.

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REFERENCES

1. P. Bazzurro, "Probabilistic Seismic Demand Analysis", Ph.D. Thesis, Stanford University, 1998.
2. N. Shome, "Probabilistic Seismic Demand Analysis of Nonlinear Structures", Ph.D. Thesis, Stanford University, 1999.
3. N. Luco, "Probabilistic Seismic Demand Analysis, SMRF Connection Fractures, and Near-Source Effects", Ph.D. Thesis, Stanford University, 2002.
4. I. Iervolino and C.A. Cornell, "Records selection for nonlinear seismic analysis of structures", *Earthquake Spectra* **21**, No. 3, 685-713 (2005).
5. G. W. Housner, "Spectrum Intensities of Strong Motion Earthquakes", *Proceedings, Symposium on Earthquake and Blast Effects on Structures*, Earthquake Engineering Research Institute (1952).
6. J. L. Von-Thun, L. H. Rochin, G. A. Scott and J. A. Wilson, "Earthquake Ground Motions for Design and Analysis of Dams", in *Earthquake Engineering and Soil Dynamics II – Recent Advance in Ground-Motion Evaluation,* Geotechnical Special Publication 20, ASCE, New York, 463-481 (1988).
7. J. W. Baker and C. A. Cornell, "A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon", *Earthquake Engineering and Structural Dynamics* **34**, 1193-1217 (2005).
8. P. Tothong and N. Luco, "Probabilistic Seismic Demand Analysis Using Advanced Ground Motion Intensity Measures", *Earthquake Engineering and Structural Dynamics* **36**, 1837-1860 (2007).
9. P. P. Cordova, G. G. Dierlein, S. S. F. Mehanny and C. A. Cornell, "Development of a Two Parameter Seismic Intensity Measure and Probabilistic Assessment Procedure", in *The second U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforce Concrete Building Structures*, Sapporo, Hokkaido 2001, pp. 187-206.
10. J. W. Baker and C. A. Cornell, "Vector-Valued Intensity Measures for Pulse-Like Near-Fault Ground Motions", *Engineering Structures* (2007), in press.
11. J. W. Baker and C. A. Cornell, "Spectral Shape, Epsilon and Record Selection", *Earthquake Engineering and Structural Dynamics* **35**, 1077-1095 (2006).
12. P. Fajfar and H. Krawinkler, "Conclusions and Recommendations. Seismic Design Methodologies for the Next Generation of Codes", A.A. Balkema 1997.
13. G Manfredi, "Evaluation of Seismic Energy Demand", *Earthquake Engineering and Structural Dynamics* **30**, 485-499 (2001).
14. A. Terán-Gilmore and J. O. Jirsa, "Energy Demands for Seismic Design Against Low Cycle Fatigue", *Earthquake Engineering and Structural Dynamics* **36**, 383-404 (2007).
15. E. Bojórquez, S. E. Ruiz and A. Terán-Gilmore, "Reliability-Based Evaluation of Steel Structures Using Energy Concepts", *Engineering Structures* (2007), in press.
16. P. Tothong, "Probabilistic Seismic Demand Analysis Using Advanced Ground Motion Intensity Measures, Attenuation Relationships, and Near Source Effects", Ph.D. Thesis, Stanford University, 2007.
17. I. Iervolino and C. A. Cornell, "Prediction of the Occurrence of Velocity Pulses in Near-Source Ground Motions", submitted, 2007.
18. I. Iervolino, G. Manfredi and E. Cosenza, "Ground Motion Duration Effects on Nonlinear Seismic Response", *Earthquake Engineering and Structural Dynamics* **35**, 21-38 (2006).
19. Y. J. Park and A. H. Ang, "Mechanistic Seismic Damage Model for Reinforced Concrete", *Journal of Structural Engineering ASCE* **111**, No. ST4, 740-757 (1985).
20. E. Cosenza, G. Manfredi and R. Ramasco, "The Use of Damage Functionals in Earthquake Engineering: A Comparison Between Different Methods", *Earthquake Engineering and Structural Dynamics* **22**, 855-868 (1993).
21. D. M. Boore and G. M. Atkinson, "Boore-Atkinson NGA Ground Motions Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameter", *Pacific Earthquake Engineering Research Center, University of California, Berkeley*, PEER Report (2007).