Journal of Earthquake and Tsunami, Vol. 2, No. 3 (2008) 241–258

UNIFORM HAZARD SPECTRA BASED ON PARK-ANG DAMAGE INDEX

DEBARATI DATTA and SIDDHARTHA GHOSH*

Department of Civil Engineering
Indian Institute of Technology Bombay
Powai, Mumbai 400076, India
sghosh@civil.iitb.ac.in

Accepted 22 December 2007

The primary emphases in the performance-based seismic design (PBSD) philosophy are in the accounting for uncertainties in seismic demand/capacity and in the better quantification of seismic damage using suitable inelastic damage parameters. Uniform hazard spectra (UHS) provide probabilistic information regarding a seismic demand on a single degree oscillator for a specific site. UHS are very good tools for probabilistic hazard estimation as intended in PBSD. In the present work, UHS are generated for Park-Ang damage index of an elastic-perfectly plastic oscillator. Park-Ang damage index takes into account the effects of both displacement ductility demand and hysteretic energy demand in low-cycle-fatigue, and therefore is a demand parameter suitable for PBSD. The UHS are generated for a specific site using artificially generated ground motions. Two types of UHS plot are illustrated. A correlation between the probability of exceedance (of certain target damage index) and stated level of structural capacity is also established. Information provided by the UHS are proposed to be used, with the aid of equivalent systems, in the development of a reliability-based seismic design framework considering Park-Ang damage index as the seismic demand parameter.

Keywords: Uniform hazard spectra; Park-Ang damage index; performance-based seismic design; inelastic response spectra; reliability-based design.

1. Introduction

Performance-based seismic design (PBSD) is a relatively new concept in earthquake resistant design of structures. It is a general design philosophy in which the design criteria are expressed in terms of achieving probabilistically defined performance objectives when the structure is subjected to stated levels of seismic hazard. The target performance for a building or its "performance objective" is defined as the "desired performance level for the building for each earthquake design level" [SEAOC Vision 2000 Committee, 1995]. The performance level describes the maximum desired extent of damage to a building, given that a specific earthquake (hazard) design level affects it. Individual performance levels (such as, "fully operational", "operational", "life-safe" etc.) are defined based on the extent of damage

*Corresponding author.

in a structure and earthquake hazard (ground shaking, ground fault rupture, soil liquefaction, lateral spreading etc.) levels are described in terms of their probability of occurrence. In order to define performance levels appropriately, PBSD emphasizes on a better quantification of seismic damage in a structure. In general, for a better assessment of seismic damage and cost effectiveness of a structure, the inelastic damage parameters are preferred to the elastic ones. The Vision 2000 document [SEAOC Vision 2000 Committee, 1995] was among the first to propose a gradual shift in seismic design methodology from the simple force-based design to the advanced displacement-based and energy-based designs of the future. Similar guidelines were also provided by ATC [1996] and FEMA [1996]. In real life, the level of seismic damage is influenced by several parameters, such as the accumulation and distribution of structural damage, failure mode of elements and components, the number of cycles and duration of the earthquake, and the acceleration levels as in the case of secondary systems. Various research works have so far focused on developing performance-based design methodologies considering improved measurement of structural damage, such as, displacement ductility [Collins *et al.*, 1996; Ghoborah *et al.*, 1997], hysteretic energy demand [Cosenza and Manfredi, 1997; Ghosh and Collins, 2006], and life cycle cost for a building [Wen, 2001].

Throughout its design life, a structure is potentially exposed to all possibilities of occurrence of ground motion intensities. A probabilistic seismic hazard analysis (PSHA) can evaluate the hazard of seismic ground motion at a site by considering all possible earthquakes in the area, estimating the associated shaking at the site, and calculating the probability of occurrences as required in PBSD. The PSHA is recognized to be the most rational means to quantify the seismic hazard at a specific site [Collins *et al.*, 1996] and most current design guidelines recognize this. In the context of PSHA, uniform hazard spectra (UHS) can provide the very essential probabilistic information required for an advanced seismic design philosophy, such as PBSD. A UHS can be very simply described as a ground hazard spectrum including probabilistic information based on the earthquake hazard. A UHS can adopt elastic as well as inelastic response parameters, and thus it can be suitably integrated in a PBSD methodology considering inelastic damage parameters.

This paper focuses on developing inelastic UHS for Park-Ang damage index based on simulated ground motion records for a specific site selected for this study. In the next section, previous research works on inelastic UHS are reviewed. Section 3 discusses the importance of proper damage indicators for seismic response of structures. A description of Park-Ang damage index and the advantages of using this index are also provided. The detailed method of construction of UHS based on Park-Ang damage index is described in Sec. 4 and sample UHS plots for different values of Park-Ang damage index are presented therein. Significant observations from these plots are discussed in Sec. 5. A correlation between the exceedance probability and damage index is established. Section 6 provides an empirical expression for the probability of exceedance of a target Park-Ang damage index. Section 7 focuses on how these UHS can be used in developing a probabilistic seismic design methodology based on Park-Ang damage index. The concluding remarks briefly state the usefulness and the shortcomings of the work presented here.

2. Uniform Hazard Spectra

A uniform hazard spectrum can be very effective for probabilistic seismic hazard analysis. As probabilistic methods of seismic design became preferred over deterministic methods, the concept of UHS became more common to mainstream research. The uniform hazard response spectrum is defined as a response spectrum with equal probability of exceedance of a certain hazard in all structural periods. A typical spectra plot consists of a set of spectrum curves with all the points on each curve corresponding to a single probability of exceedance of the concerned hazard (for example, Fig. 1). The hazard may be of several types. For example, it can be the probability of exceeding a certain spectral acceleration (S_a) or the probability of exceeding a certain target ductility demand (μ), for an elastic or inelastic single degree of freedom (SDOF) system.

Different methods of generation of UHS are available in existing literature. For example, McGuire [1974] used attenuation equations describing the variation of response of a SDOF oscillator with parameters such as the magnitude and the source-to-site distance. He combined these equations with probability density functions for magnitude and distance to determine the SDOF response level corresponding to a target exceedance probability. This methodology was used to generate UHS for oscillators with linear elastic restoring forces. Sewell and Cornell [1987] extended this methodology to calculate the ordinates of UHS for inelastic oscillators with nonlinear restoring forces. In their procedure, elastic response ordinates were scaled by

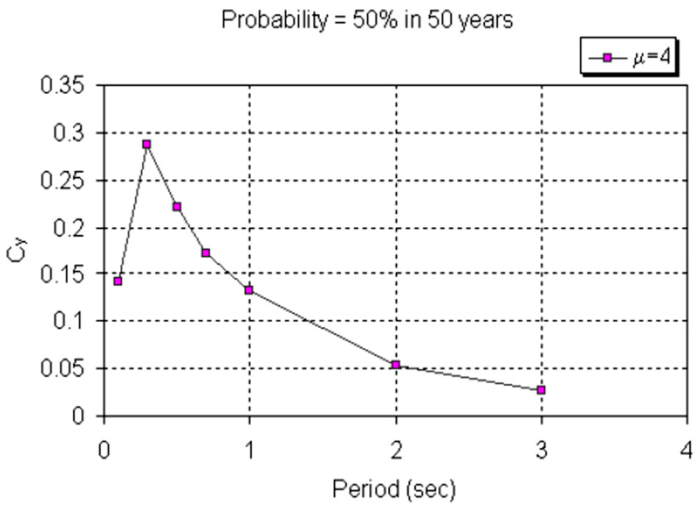


Fig. 1. UHS for displacement ductility demand ($\mu = 4$) [Collins *et al.*, 1996].

reduction factors which were functions of the level of inelastic deformation, the frequency of the system and other parameters. For constructing such spectra, a large number of ground motions, enough to represent all possible seismicity at the site should be considered. This basic methodology, with minor variations, was applied to construct UHS for spectral acceleration for various regions all over the world, as reported by many researchers [Marin *et al.*, 2004; Ghosh, 2006; Das *et al.*, 2006].

Using another method, Collins *et al.* [1996] simulated artificial ground motion data for a certain area depending upon soil class and other tectonic characteristics of a specific site, and obtained the response of a structure subjected to these ground motions. Adopting a failure criterion for the response and measuring the number of times the response exceeded that criterion, the statistics for failure was obtained. The probabilistic information was provided by the set of simulated ground motion data itself. The UHS were generated considering all the simulated ground motions. The UHS, thus generated, provided probabilistic structural response information, where the source of uncertainty in ground motion was the variation in different tectonic features. This approach eliminated the need for empirical relations describing the variation of spectral response (and/or spectral reduction factors) with magnitude, distance, etc. although it was more computation-intensive. Collins *et al.* [1996] generated artificial ground motion data using this method for a site near Los Angeles, USA. Assuming the seismic hazard at the site to be dominated by the seismicity of the region within a 150 km radius of the site, a very large set of artificial ground motion data was generated. Both elastic and inelastic responses of SDOF systems under these synthetic ground motions were obtained and from the response statistics, UHS were generated. Figure 1 shows a sample UHS for displacement ductility demand, generated using this method. Later, Ghosh and Collins [2006] generated UHS for normalized hysteretic energy demand (E_N) for the same site. Figure 2 shows a sample UHS plot for E_N.

Although, displacement ductility and hysteretic energy demands are thought to be very good measures of damage in a structure, researchers have also proposed other damage indices, which are claimed to be better representations of structural damage. Such indices are discussed in the next section.

3. Damage Index

One of the main tasks in PBSD is to choose a suitable damage parameter in a way so that it can give a realistic measurement of the seismic damage in a structure. For structural analysis and design, damage can be quantified in terms of a numerical "damage index." A damage index can be based, for example, on the results of a nonlinear dynamic analysis, on the measured response of a structure during an earthquake, or on the comparison of a structure's physical properties before and after an earthquake. Many of the commonly used damage indices are dimensionless parameters intended to range between 0 for the undamaged (elastic) state and 1

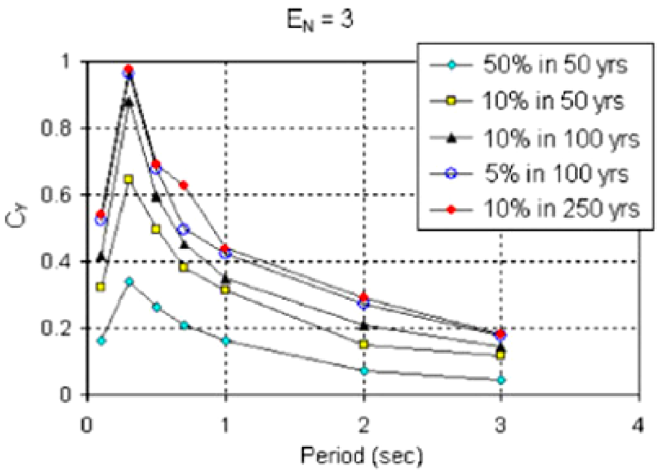


Fig. 2. UHS for normalized hysteretic energy demand ($E_N = 3$) [Ghosh and Collins, 2006].

for a collapsed state of a structure, with intermediate values giving some measure of the degree of damage [Williams and Sexsmith, 1995].

Two of the earliest and simplest forms of damage indices are interstory drift and ductility. Particularly in the inelastic range, the structural demand can be effectively expressed in terms of displacement ductility (μ). However, it was later argued that ductility or displacement/drift cannot take into account the effect of repeated load reversals on a structure during the earthquake. In other words, the low-cycle fatigue effect cannot be considered in ductility. Only the energy accumulated in the structure in inelastic range of response or, simplistically, the number of load reversals can account for that [Ghosh and Collins, 2006]. In the recent years, energy-based seismic design is gaining importance since it can account for the cumulative structural damage due to an earthquake. Hysteretic energy demand (E_h) can be considered as an effective parameter to represent the cumulative structural damage potential of the earthquake.

However, since a structure is weakened or damaged by a combination of stress reversals and high stress excursion, any damage criteria should include both the effects of maximum response and the effect of repeated cyclic loading. Consistent with the dynamic behavior, Park and Ang [1985] expressed seismic structural damage as a linear combination of the damage caused by excessive deformation (ductility) and that contributed by the effect of repeated cyclic loading (hysteretic energy). In terms of damage index, this is expressed as:

$$D_{PA} = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int \mathrm{d}E. \tag{1}$$

For this equation, Q_y is replaced by Q_u, if Q_u is smaller than Q_y. The non-negative parameter β represents the effect of cyclic loading on structural damage. This parameter is determined experimentally [Park *et al.*, 1987]. A more recent work by van de Lindt [2005] on damage based reliability of wood frame structures described how this parameter can be calibrated based on experimental results. The structural damage index (D_{PA}) is a function of the responses δ_M and $\mathrm{d}E$ that are dependent on the loading history. The parameters β, δ_u, and Q_y are structure specific and are independent of the loading history. It can be noted that the first term in the Park-Ang damage index is the ratio of the ductility demand ($\mu = \delta_M/d_y$) to ductility capacity ($\mu_c = \delta_u/d_y$). The second term represents the cumulative energy dissipation, normalized to the plastic strain energy at maximum monotonic displacement (with some factors). $D_{PA} \geq 1.0$ signifies complete collapse of the structure. The cyclic loading effect at different deformation levels is assumed to be uniform [Park and Ang, 1985]; that is, no strength or stiffness degradation is considered in repeated load-deformation cycles. It should be noted here that latter research works proposed variations of Eq. (1) for defining Park-Ang damage index, depending on the structure type and configuration [Kunnath *et al.*, 1992; Fajfar and Gašperšič, 1996]. Although the results presented hereafter in this article are based on the definition presented in Eq. (1), the general method proposed here can be easily adopted for any variations of Eq. (1).

4. UHS Based on Park-Ang Damage Index

This section discusses the construction of UHS for Park-Ang damage index (D_{PA}) using simulated ground motion records. These are the artificial ground motions that were generated by Collins *et al.* [1996] for a site near Los Angeles, USA, at the geographical location of 118° West and 34° North. The surrounding region of 150 km radius was subdivided into "seismic zones" based on the zones used by the U.S. Geological Survey in its seismic hazard studies of the region [Algermissen *et al.*, 1990]. Earthquakes were assumed to occur equally likely at anywhere within each zone. The soil conditions at the site were assumed to be consistent with the S_2 soil class defined in the NEHRP Recommended Provisions [BSSC, 1992].

Collins *et al.* [1996] assumed that the earthquakes were exponentially distributed with respect to their magnitude and interoccurrence time. This assumption implied that the number of earthquakes which occur within a given time-span follows a Poisson distribution. The Poisson model is believed to be a "sufficiently good" stochastic model for engineering applications for the Los Angeles metropolitan area [Todorovska, 1994]. Within each zone, earthquakes were assumed to occur at discrete points. Epicentral distance was the only source-to-station distance modeled in the simulation. The peak ground acceleration for each simulated record was determined using the regression equation proposed by Boore *et al.* [1993]. The frequency content of each simulated record was modeled using the regression equation for Fourier amplitude spectrum proposed by Trifunac [1993], which describes the variation of frequency content with magnitude, distance and soil conditions.

Based on these assumptions, Collins *et al.* [1996] generated a set of 1292 simulated ground acceleration records spanning over eight hundred 10-year periods. This set of artificial ground motion records was used for constructing UHS based on ductility demand (μ). The same set of simulated ground motions was also used later to construct hysteretic energy based UHS [Ghosh and Collins, 1996], and both types of UHS were used for developing reliability-based design methods.

In this study, to generate the UHS based on D_{PA}, an elastic-perfectly plastic SDOF oscillator is analyzed for a range of yield force coefficient (C_y) values. C_y is defined as the ratio of the spring force at yield displacement to the weight of the oscillator. Mathematically, it is expressed as

$$C_y = \frac{Q_y}{W} = \omega_n^2 \frac{d_y}{g}. \tag{2}$$

The non-dimensional parameter C_y can be treated as a representation of the "yield strength" of the system.

For the generation of UHS based on D_{PA}, a ductility capacity (μ_c) of the structure needs to be assumed. Then, a range of time periods (T) is considered for the inelastic (elastic-perfectly plastic) single degree oscillator. At each time period, a number of C_y values are assumed. At each C_y, nonlinear time history analyses are carried out for the SDOF system for all the ground motion records generated by Collins *et al.* [1996], and D_{PA} for each ground motion is obtained from the response time history following Eq. (1). The number of cases reporting an exceedance of a certain value of D_{PA} is recorded from the analysis results. From this response statistics of D_{PA}, the annual exceedance probability of that certain damage index is obtained. Inversely, C_y value for a selected "standard" exceedance probability is obtained by linear interpolation of known C_y values for the exceedance probabilities already obtained. This process is repeated for all exceedance probabilities at a particular time period (T), and then this whole procedure is repeated for all the considered time periods. This method is presented in a flowchart form in Fig. 3 (the term NLDA in Fig. 3 stands for nonlinear dynamic analysis).

In the present work, three different values of displacement ductility capacity ($\mu_c = 2$, 4 and 6) are considered for calculating D_{PA}. These ductility values represent comparatively low, moderate and high ductility capacity of the structure, respectively. For each of the ductility values, seven different time periods (0.1, 0.3, 0.5, 0.7, 1.0, 2.0 and 3.0 seconds) of the inelastic SDOF system are selected for obtaining the UHS plots. The value of the non-dimensional parameter β in D_{PA} is adopted as 0.025 following an earlier observation on steel structures [Park *et al.*, 1987]. From the response statistics for all the 1292 ground motions, 10-year exceedance probabilities (p_{10}) for several target D_{PA} values are calculated by treating each 10-year period as an "independent trial" of a binomial distribution [Ang and Tang, 1975]. Five target probabilities of exceedance, as shown in Table 1, are considered for defining the hazards. Table 1 also provides the corresponding

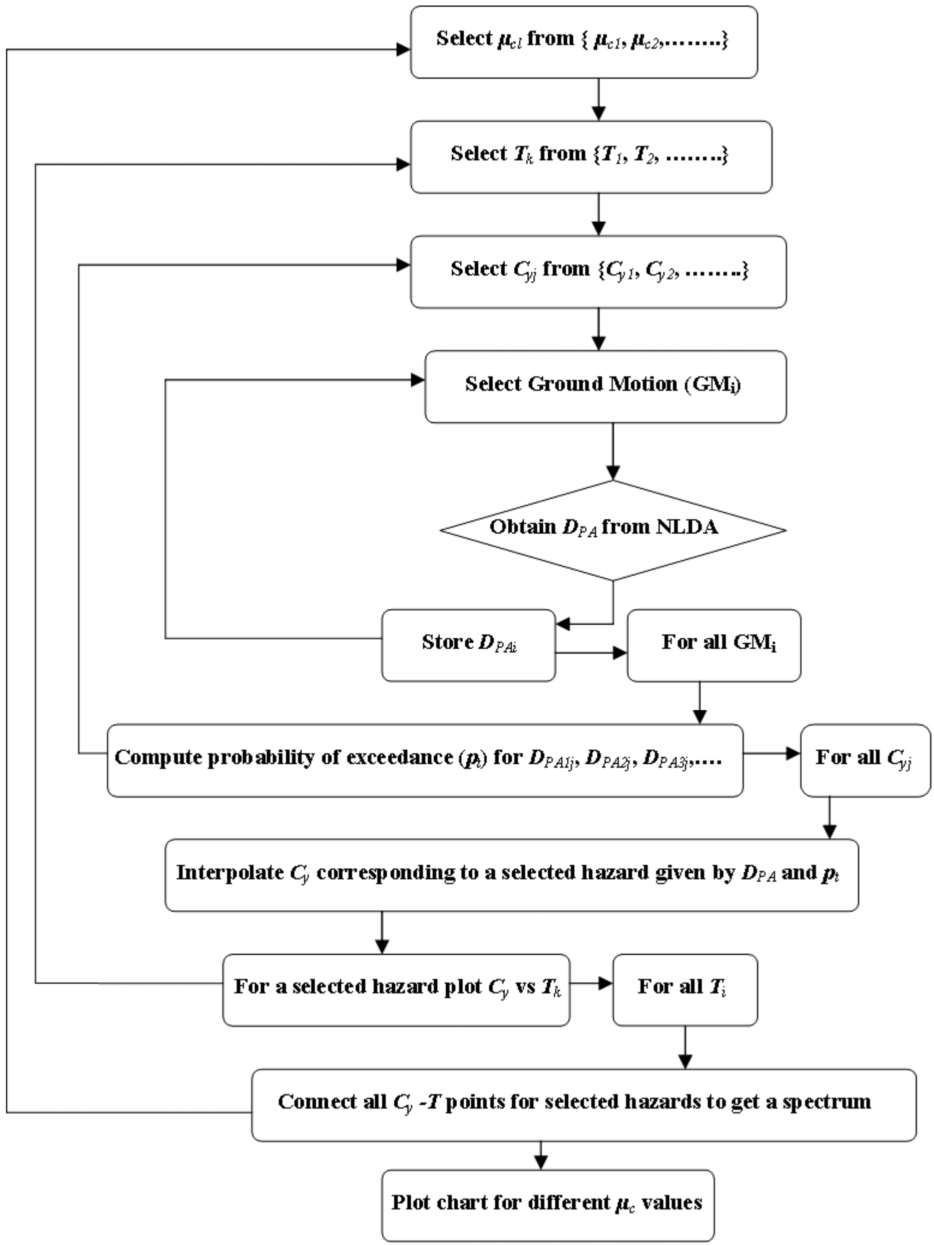


Fig. 3. Flowchart presenting detailed procedure for constructing UHS based on D_{PA}.

target annual probability values (p_t). These exceedance probabilities correspond to "occasional", "rare", "very rare" and "extreme" hazard levels, respectively, as per the Vision 2000 document [SEAOC Vision 2000 Committee, 1995]. Similar definitions of hazard levels can be found in other literatures as well [Ghoborah, 2001]

Table 1. Standard exceedance probabilities and corresponding annual probability values.

Target Exceedance Probability	Annual Exceedance Probability (p_t)
50% in 50 years	1.377×10^{-2}
10% in 50 years	2.105×10^{-3}
10% in 100 years	1.053×10^{-3}
5% in 100 years	5.128×10^{-4}
10% in 250 years	4.214×10^{-4}

and some of these hazard definitions are already in use through design guidelines [ICC, 2006]

Annual exceedance probabilities are obtained from 10-year exceedance probabilities, using the relation

$$p_t = 1 - \exp\left[\frac{\ln(1 - p_{10})}{10}\right]. \tag{3}$$

C_y for a target exceedance probability is calculated using linear interpolation between the C_y values used for the dynamic analysis. Thus, the C_y required for a uniform hazard defined in terms of D_{PA} and p_t (e.g. 10% probability of exceeding $D_{PA} = 0.5$ in 100 years) is obtained. This procedure is repeated at seven selected time periods and the required C_y values corresponding to a certain hazard are plotted against the natural periods of the SDOF oscillator. Joining the points describing the same hazard for different periods, a uniform hazard spectrum is obtained. For example, Fig. 4 shows UHS plots for D_{PA} for a selected displacement ductility capacity, $\mu_c = 2$. Figure 5 shows UHS, at different values of μ_c, for $D_{PA} = 1$, that is the Park-Ang damage index corresponding to "collapse".

There are two different ways to represent these uniform hazard spectra in a plot. A spectra plot can consist of several hazard curves corresponding to a fixed value of damage index but for different probabilities of exceedance. Figures 4 and 5 show this type of representation of UHS. Alternatively, a spectra plot may contain hazard curves corresponding to a certain probability of exceedance for different values of damage indices. Figure 6 shows this type of representation of UHS at $\mu_c = 2$.

5. Observations and Discussion

The UHS plots shown in Figs. 4–6 represent probabilistic seismic demand on an inelastic SDOF structure. For a particular displacement ductility capacity (μ_c), plots are obtained for different probabilities of exceedance of a certain damage index and vice versa. For a particular μ_c value, target damage index values are selected to represent the response range between the elastic limit to collapse. For example, for $\mu_c = 2$ (Fig. 4), $D_{PA} = 0.5$ signifies a damage state at the elastic limit and $D_{PA} = 0.75$ signifies a damage state in the middle of elastic limit and collapse. For all the three cases shown in Fig. 5, $D_{PA} \geq 1.0$ signifies a total collapse. It can be observed in Fig. 4 that for a fixed exceedance probability and time period

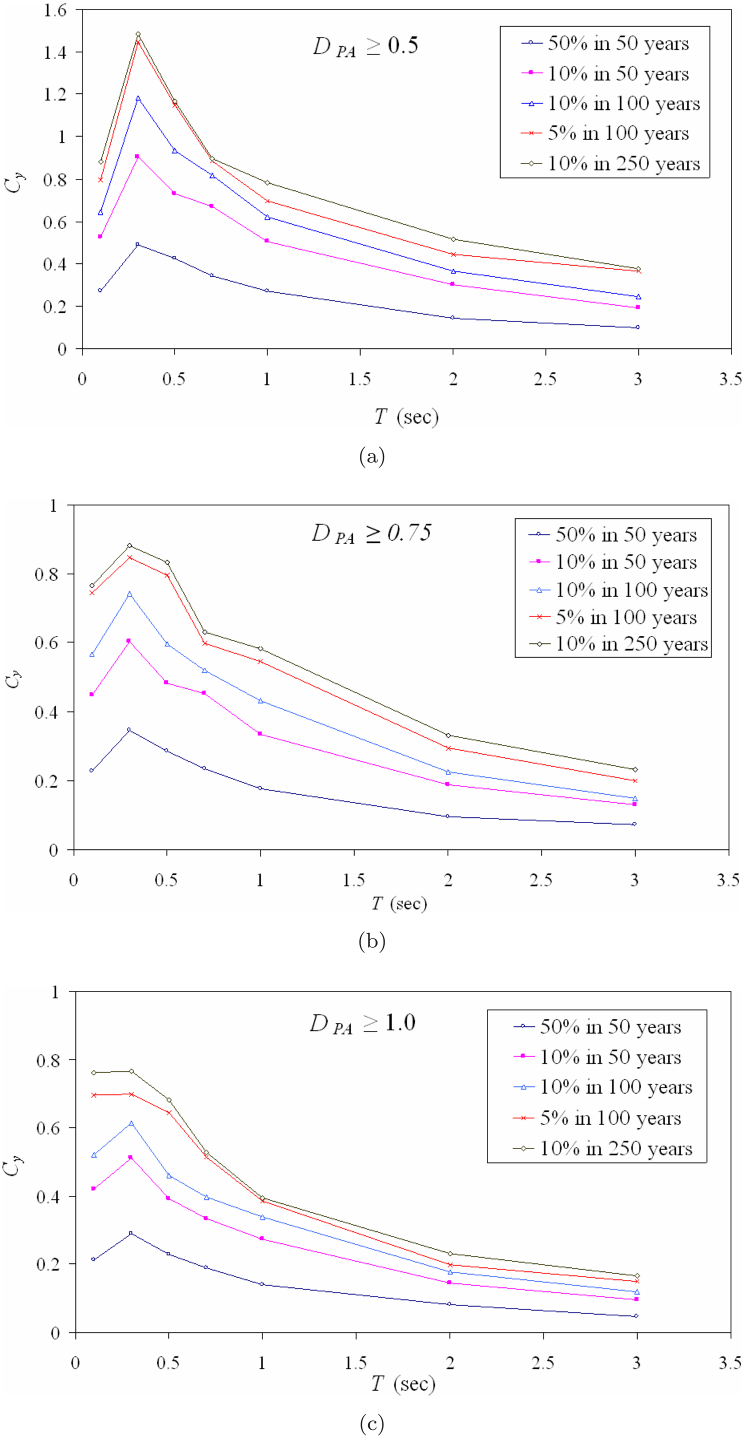


Fig. 4. UHS for (a) $D_{PA} \geq 0.5$, (b) $D_{PA} \geq 0.75$, and (c) $D_{PA} \geq 1.0$, at $\mu_c = 2$.

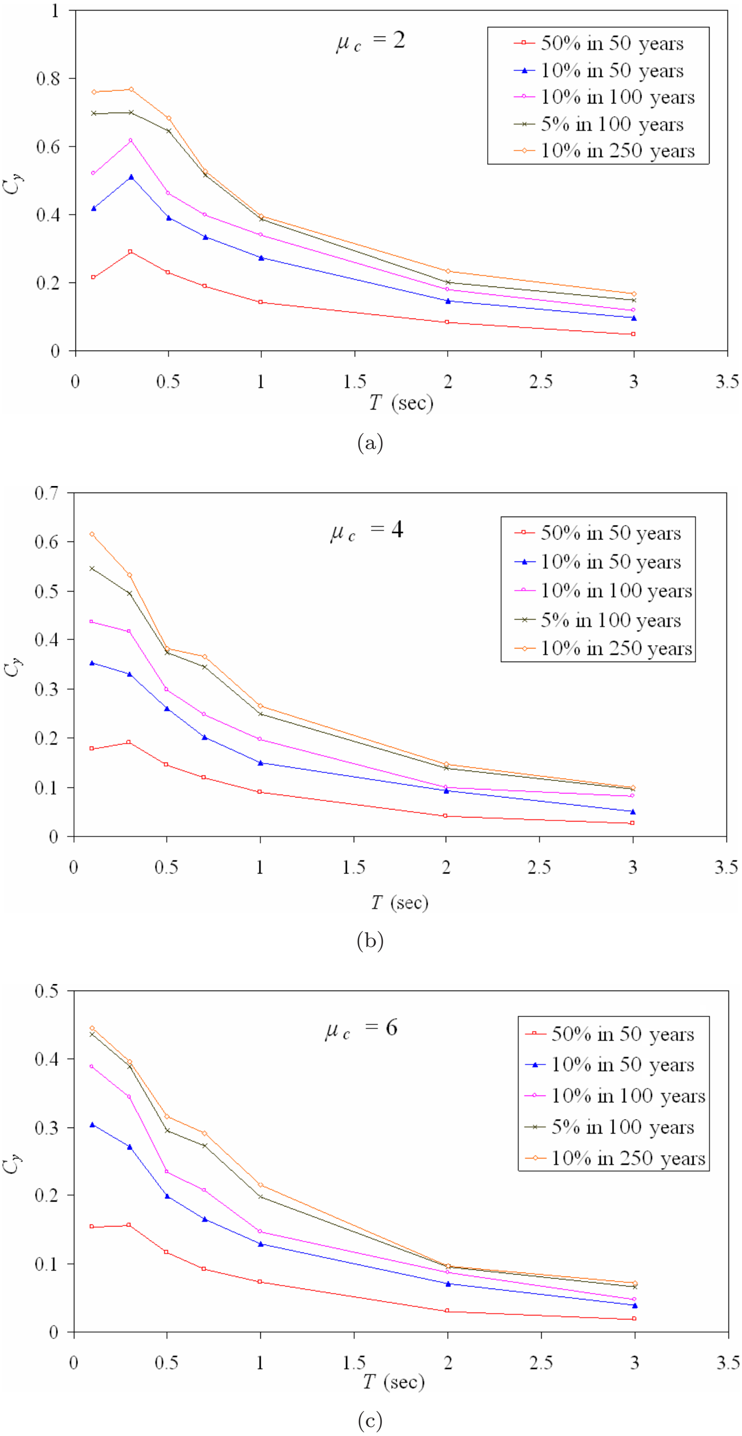
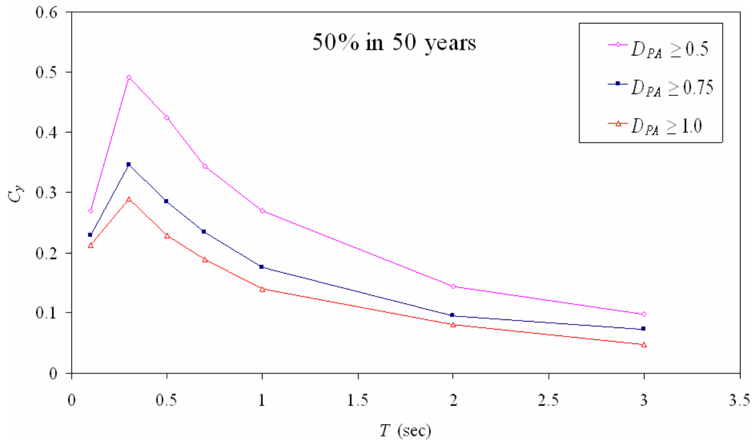
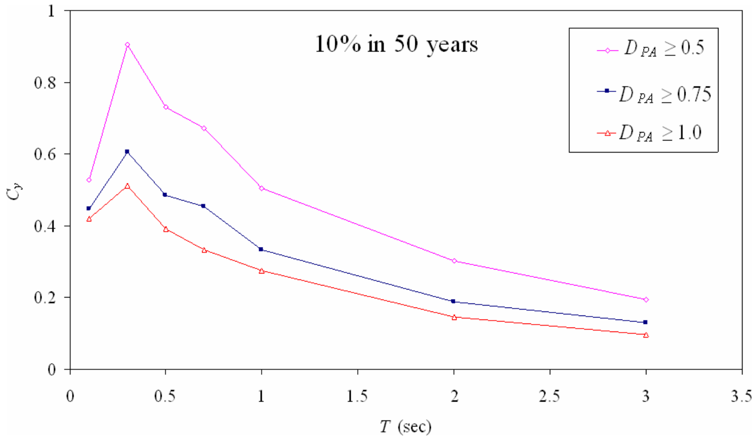


Fig. 5. UHS at (a) $\mu_c = 2$, (b) $\mu_c = 4$, and (c) $\mu_c = 6$, for $D_{PA} \geq 1.0$.



(a)



(b)

Fig. 6. UHS for exceedance probabilities (a) 50% in 50 years and (b) 10% in 50 years, at $\mu_c = 2$.

the required yield force coefficient (C_y) increases as the value of D_{PA} decreases. This observation justifies the general idea that possibility of damage is less to the structures of higher capacity (here, yield strength). Similar information obtained from earlier works (e.g. Fig. 2) was useful in developing reliability-based design checking methodologies [Collins *et al.*, 1996; Ghosh and Collins, 2006].

A comparative study of the individual curves in Fig. 5 shows that for an increased ductility capacity, exceedance probability of collapse ($D_{PA} \geq 1.0$) can be maintained at the same level with a reduced yield strength. This matches with the deterministic concept that with higher ductility capacity, a structure can resist collapse at lower yield strength. This observation also supports the idea that for the same yield strength, higher ductility capacity of structure leads to less seismic damage.

Figure 6 presents the second type of representation of UHS. Among the five different probabilities of exceedance mentioned earlier in Table 1, two (50% in 50 years and 10% in 50 years) are shown separately. The 10% in 50 years hazard represents the commonly used design level for ground motion, as in IBC 2006 [ICC, 2006]. The 50% in 50 years hazard represents a more frequent earthquake meant for stricter performance objectives. From the UHS plots presented here, it is observed that for a fixed D_{PA} and time period, the probability of exceeding the damage index decreases as the required yield force increases.

Similar observations were noticed in UHS based on ductility and hysteretic energy demand, and these relations were used effectively in developing ductility-based and hysteretic energy-based design methods [Collins *et al.*, 1996, Ghosh and Collins, 2006]. The similar observation for Park-Ang damage index-based UHS is also expected to be useful for developing a damage index-based probabilistic design method.

It should be noted here that an inelastic UHS based on D_{PA} represents ductility demand (μ) with respect to its capacity (μ_c), whereas the earlier UHS [e.g. Sewel and Cornell, 1987; Collins *et al.*, 1996; Ghosh and Collins, 2006] did not require any such capacity measurement. These UHS based on Park-Ang damage index is expected to provide better quantification of probabilistic seismic demand leading to better design of earthquake resistant structures.

6. Empirical Expression for Demand Probability

An empirical relationship between the structural strength (capacity), as represented by C_y, and the probability of exceedance of a target damage index ($\mathrm{D}_{PA_{target}}$) is established based on the UHS data. Of the several empirical models investigated, the model which seems to provide the best fit overall is of the following form:

$$\mathrm{P}(D_{PA} > D_{PA_{target}} \text{ given } C_y) = \exp\{-a(C_y)^b\}. \tag{4}$$

In Table 2, values of the function parameters a and b are tabulated for each period and target damage index, for a ductility capacity $\mu_c = 2$. A sample comparison plot of exceedance probability versus C_y is also presented in Fig. 7. Similar empirical expressions for the probability of exceedance with respect to C_y were effectively used

Table 2. Values for function parameters a and b for ductility capacity $\mu_c = 2$.

D_{PA}		Time Period, T (sec)						
		0.1	0.3	0.5	0.7	1.0	2.0	3.0
0.5	a	8.300	6.091	6.896	7.551	8.403	10.20	12.53
	b	0.4734	0.4685	0.4943	0.4904	0.4766	0.4268	0.4530
0.75	a	8.969	7.789	8.711	9.020	9.583	12.54	15.72
	b	0.4774	0.5113	0.5171	0.4788	0.4443	0.438	0.4602
1.00	a	9.242	8.641	9.634	10.10	10.84	16.46	16.93
	b	0.4741	0.5146	0.5101	0.4813	0.4511	0.5042	0.4352

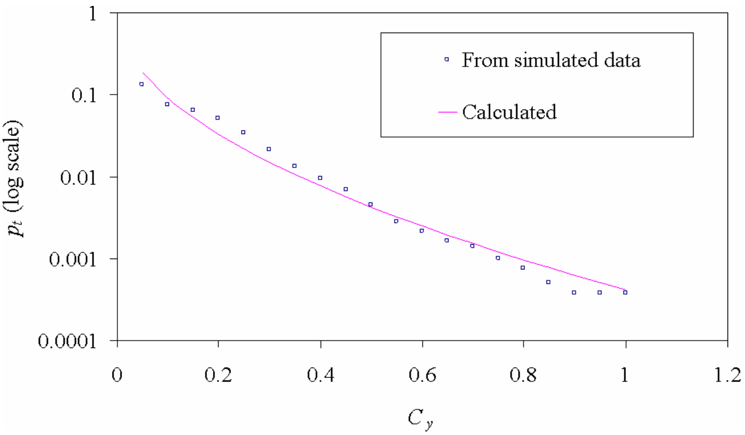


Fig. 7. Comparison between p_t from the simulated data and from the empirical function of Eq. (4) for $T = 0.3$ s and $D_{PA} = 0.75$, at $\mu_c = 2$.

in developing reliability-based design methodologies [Collins *et al.*, 1996; Ghosh and Collins, 2006].

7. Requirements for a Design Methodology Based on Target D_{PA}

The UHS described in this paper present the demand on an inelastic SDOF oscillator. To use this demand information for the design of real structures, some technique is required to relate the response of a SDOF system to that of a multi-degree of freedom (MDOF) system. "Equivalent" or "generalized" SDOF systems can be used to obtain useful information about the response of a MDOF system. However, the MDOF response can be obtained only in a statistical sense by applying a suitable bias factor on the equivalent SDOF (ESDOF) response. Uncertainties involved in estimating the MDOF response must be accounted for in developing a design checking equation for a selected target performance criterion. A recent study by Datta and Ghosh [2008] investigating the possibility of developing ESDOF systems to estimate D_{PA} for multi-story steel moment resisting frame systems shows promising results in this regard. For the 3-, 9- and 20-story steel moment frames tested, subject to 28 strong motion records, the bias (defined as the ratio of the MDOF-based D_{PA} to the ESDOF-based D_{PA}) is found to have mean values close to its ideal value 1.0 and low coefficients of variation. Figure 8 shows a scatterplot comparing the estimates from the 3-story MDOF system and the corresponding ESDOF system for 28 ground motion records and three μ_c values. Each point on the plot represents a single earthquake and a ductility capacity. The diagonal line across the plot implies an equal response from the ESDOF system as of the actual MDOF model. Although the level of accuracy decreases slightly from low-rise to high-rise frames, these results indicate to a clear possibility of developing a design methodology based on target D_{PA}, where the UHS discussed in this paper can be

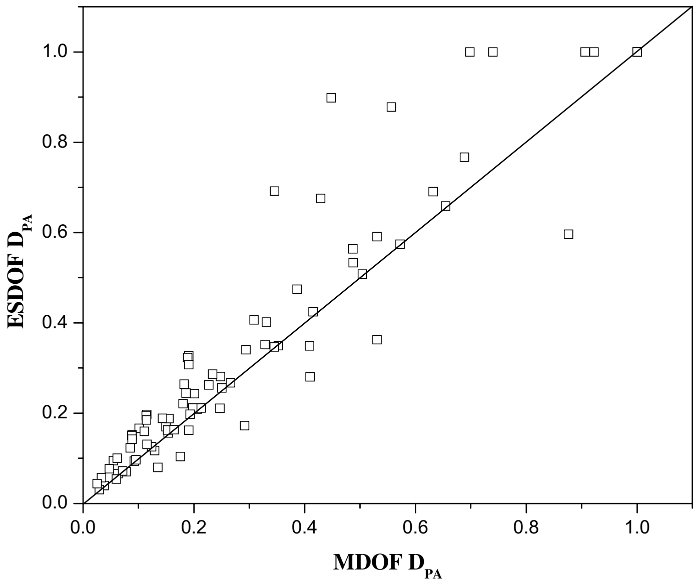


Fig. 8. Scatterplot comparing the D_{PA} estimates of the 3-story MDOF system and of its equivalent system [Datta and Ghosh, 2008].

effectively utilized. The bias statistics generated in this way can be useful in incorporating the uncertainty information (along with the probabilistic information from UHS based on D_{PA}) in a reliability-based design framework.

8. Concluding Remarks

Uniform hazard spectra based on D_{PA} for a specific site are generated and presented in this paper. These spectra provide an effective means of probabilistic seismic hazard estimation that suits the purpose of a performance-based seismic design methodology. These UHS can be presented in two different ways depending on particular design application. The UHS plots presented in this paper provide probabilistic estimation of the response of an elastic-perfectly plastic SDOF system in terms of Park-Ang damage index (D_{PA}).

The formulation of D_{PA} requires a specific pre-selected displacement ductility capacity (μ_c) of the SDOF system. In the present work, D_{PA} based UHS are generated for systems with low, medium and high ductility capacity (μ_c) values. It is observed that for a system with known time period (T) and ductility capacity (μ_c), the exceedance probability of a certain D_{PA} increases as the C_y value decreases. The empirical relationship of Eq. (4), providing the same information as the UHS, can be effectively used for developing a design checking equation for a selected target performance criterion.

The demand information provided by the UHS, which is essentially for an inelastic SDOF oscillator, can be used for the design of real structures by using an equivalent system scheme. The information from equivalent system bias statistics along with the information from Eq. (4) are useful in developing a reliability-based design framework. The concept presented in this paper, thus, is a significant step toward developing a damage index-based, reliability-based design procedure. However, some important issues require further study as discussed next.

There are simplified assumptions in the simulation procedure to generate artificial ground motion data. For example, the effects of directivity were not considered in the simulation process while significant directivity effects can be observed near the active faults [Somerville *et al.*, 1995]. Also the UHS are derived from time-intensive simulation procedures for only one specific site. In practice, it will be necessary to obtain UHS information based on hazard maps for an entire region or country. Such issues, related to probabilistic hazard estimation and presentation of the results in a format suitable for code implementation, need detailed exploration. Also, the spectra presented here are based on a simple elastic-perfectly plastic force displacement model in the SDOF oscillator. Although this does not account for phenomena like strain-hardening and strength/stiffness degradation, which are commonly observed in many experimental investigations, the generic method proposed here can be extended to address these phenomena.

List of Symbols

a, b = Function parameters used in expressing the exceedance probability for D_{PA}
C_y = Yield force coefficient
$\mathrm{d}E$ = Incremental hysteretic energy
D_{PA} = Park-Ang damage index
$D_{PA_{target}}$ = Target Park-Ang damage index
d_y = Yield displacement
E_h = Hysteretic energy demand
E_N = Normalized hysteretic energy demand
p_{10} = 10-year exceedance probability
p_t = Annual exceedance probability
Q_y = Calculated yield strength of structure
S_a = Pseudo spectral acceleration
T = Time period(s) of an oscillator
W = Seismic weight of an oscillator
β = Non-negative parameter representing the effect of cyclic loading in Park-Ang damage index
δ_M = Maximum deformation demand under earthquake
δ_u = Ultimate deformation capacity under monotonic loading
μ = Displacement ductility demand
μ_c = Displacement ductility capacity
ω_n = Natural frequency of an oscillator

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