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PSHA-based scenario earthquakes and earthquake weighting factors

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ABSTRACT

The nuclear industry in North America has adopted a performance-based approach to define the site-specific earthquake ground motion. This requires the development of seismic hazard information base and deaggregation of scenario earthquakes for a site of interest. Existing seismic hazard deaggregation (SHD) procedures typically determine a single scenario earthquake towards a specific ground motion level at a particular frequency content. To have a more complete understanding of the most contributing events towards different ground motion levels and at different frequencies, multiple SHDs are performed separately.

This paper presents a new SHD procedure to determine a set of scenario earthquakes, encompassing from small near-field event to large far-field event. A more complete picture of the contributing events to seismic hazard at the site is provided. To apply a set of scenario earthquakes in seismic analysis, earthquake weighting factor assigned to each earthquake scenario is defined. The scenario earthquakes with the associated weighting factors collectively replicate seismic hazard curve in the probability range of $1E-3 \sim 1E-6/\text{yr}$ that contributes most to seismic risk for nuclear applications. A realistic example is presented to demonstrate the effectiveness of the proposed SHD procedure. Useful insights gained from the SHD results are discussed.

1 INTRODUCTION

A performance-based approach was adopted for the development of site-specific earthquake ground motion (USNRC 2007) and seismic design of structures and components for nuclear facilities (ASCE 2005) in North America. Probabilistic Seismic Hazard Analysis (PSHA) (Cornell 1968; McGuire 2004) is required to provide the seismic hazard information base for the site. A combined probability of exceedance of a specific ground motion level is evaluated in a PSHA by integrating over all possible earthquake occurrences. Proper seismic design ground motion level is then defined based on the PSHA results. The PSHA, which provides a combined probability of exceedance of a particular ground motion level, is an aggregation procedure. The relative contribution from individual events is somewhat blurred in a PSHA.

To better understand the earthquake characteristics, it is often required to identify the dominant event for a reference ground motion level. This information is typically obtained from a seismic hazard deaggregation (SHD) (McGuire 1995; Bazzurro and Cornell 1999). The SHD graphically shows the relative contributions to hazard from the primary ground-motion predictor variables, e.g., earthquake magnitude M , source-site distance R , and ground-motion variability ϵ . A scenario earthquake, either an M - R pair or an M - R - ϵ triplet, is then extracted in a weighted average sense. The scenario earthquake is the representative earthquake threat to the site at the reference hazard level.

The ASME/ANS PRA standard (ASME 2013) for nuclear applications requires both the magnitude-distance deaggregation and seismic source deaggregation in seismic hazard analysis for PRA Capability Category III. The magnitude-distance deaggregation allows the analyst

to characterize the nature of ground motion properly for use in the response and fragility analysis of structures and components (ASME 2013).

In practice, applications of the SHD-based single earthquake scenario for engineering purposes may be challenged due to some inherent limitations of the current procedure:

- ✚ First, the single scenario earthquake extracted may not necessarily be a practical earthquake for the site. This is particularly true when the site have both a near-field source that produces only small earthquakes and a far-field source that produces only large earthquakes. The single scenario earthquake, determined in a weighted average sense, is unlikely to be a physically feasible earthquake threat to this site.
- ✚ Second, the scenario earthquake is extracted from a particular ground motion level. To obtain scenario earthquakes towards multiple ground motion levels, multiple SHDs have to be performed separately. For different ground motion levels, the extracted scenario earthquakes can vary significantly.
- ✚ Third, a single scenario earthquake does not provide a complete picture of all significant contributing events towards the hazard and may mask some significant events. As a result, no information on competing seismic events is retained.

To overcome the limitations identified above, this paper introduces a new SHD procedure, which consists of deaggregating a limited set of scenario earthquakes in terms of magnitude M , source-site distance R , and the associated rate of occurrence. The objectives of this study include:

[†] Views expressed in this paper are those of the author and do not necessarily reflect those of CNSC.

- ✚ Extend the concept of SHD to include a variety of practical contributing scenarios, thus avoiding rough averaging of all contributing events.
- ✚ Determine a set of scenario earthquakes that collectively replicate the standard hazard curve in the 1E-3~1E-6/yr probability range, thus avoiding repetitions of SHD at different hazard levels.
- ✚ Represent seismic hazard using the set of scenario earthquakes and provide meaningful insights into the seismic threat of the site of interest.

This paper is organized as follows: the basics of PSHA are briefly described in Section 2. Existing SHD procedures are reviewed and limitations in hazard representation by a single scenario earthquake are discussed in Section 3. A new SHD procedure is presented in Section 4 that determines a set of scenario earthquakes and defines the rate of occurrence for each scenario. A practical example is presented in Section 5 to demonstrate the effectiveness of the proposed procedure in identifying scenario earthquakes. Conclusions are drawn in Section 6.

2 BASICS OF PSHA

Probabilistic seismic hazard analysis (PSHA) (Cornell 1968; McGuire 2004) is a probabilistic method for quantifying the ground-motion hazard in terms of a selected ground motion parameter (GMP) at a site of interest. The current PSHA framework is referred to as the Cornell-McGuire PSHA. By taking into account all possible earthquake occurrences from all surrounding sources, a combined annual probability of exceedance of a specific GMP value at the site is estimated in a PSHA.

Take spectral acceleration $S_a(f)$ at vibration frequency f as the GMP, and assume that earthquake magnitude M and source-site distance R are statistically independent in a well-defined seismic source. The annual probability of $S_a(f)$ exceeding a threshold s at the site is given by

$$\lambda_s = \sum_{i=1}^{N_s} v_i \left\{ \iint_{r, m} P\{S_a(f) > s | m, r\} f_M(m) f_R(r) dm dr \right\}_i, \quad (2.1)$$

where N_s is the total number of seismic sources, v_i is the mean rate of earthquake occurrence with magnitude above m_{\min} for source i , and $f_M(m)$ and $f_R(r)$ are the probability density functions of magnitude M and source-site distance R , respectively. $P\{S_a(f) > s | m, r\}$ is the probability distribution of $S_a(f)$ given the occurrence of a scenario earthquake (i.e., a m - r pair), which reflects the ground motion randomness.

Given a scenario earthquake, $S_a(f)$ is assumed to follow the lognormal distribution $LN(\mu, \sigma^2)$ with parameters μ and σ provided by an appropriate set of ground-motion prediction equations (GMPE). GMPE models the functional dependency of ground motion intensity on the primary predictor variables, i.e., earthquake magnitude m

and source-site distance r , which takes the following functional form

$$\ln S_a(f) = f(m, r, f, \theta) + \sigma(m, f) \varepsilon(f), \quad (2.2)$$

where $f(m, r, f, \theta) = \mu$ is the expected value of the equation and $\varepsilon(f)$ is the number of standard deviations $\sigma(m, f)$ that $\ln S_a(f)$ deviates from $f(m, r, f, \theta)$.

The result of a PSHA is typically represented by a seismic hazard curve of annual probability of exceedance plotted against the selected GMP. This curve is developed by performing PSHA for many GMP s values, the range of which should cover near zero s value to very large s value, e.g., 10 g . Seismic hazard curve provides an estimate of the exceedance probability of a specific ground motion intensity in future earthquake events based on current collective knowledge from all informed scientific communities.

3 SHD-BASED SINGLE SCENARIO EARTHQUAKES

This section describes the general SHD procedure, SHD-based single earthquake scenarios, and regulatory requirements on identifying earthquake scenarios in each of the following subsections.

3.1 General SHD Procedure

SHD (McGuire 1995; Bazzurro and Cornell 1999) was introduced to provide insights into the most contributing events to seismic hazard at a reference probability level. It is typically performed to characterize the primary random variables that impact most to the hazard, e.g., earthquake magnitude M , source-site distance R , and ground-motion randomness ε . SHD has also been used to characterize the mean rate of occurrence ν (Ni 2012) and the GMPEs used (Lin and Baker 2011). Deaggregation of hazard has become a required part in modern PSHA studies for nuclear power plant sites in that it provides information useful for review of the PSHA results and insight into sources that most impact the hazard at a site (USNRC 2007).

The most widely use of a SHD has been to determine the magnitude-distance distribution for hazard contribution and to extract a controlling event (scenario earthquake). The general SHD procedure is summarized as follows:

- 1) The contribution from all earthquake occurrences in all sources towards spectral acceleration s is deaggregated into small intervals $m_{x-1} \leq m \leq m_x$ and $r_{y-1} \leq r \leq r_y$ ($1 \leq x \leq x_N$ and $1 \leq y \leq y_N$, where x_N and y_N are the total number of intervals divided for m and r , respectively), which is given by

$$\lambda_{s,x,y} = \sum_{i=1}^{N_s} v_i \left\{ \int_{r_{y-1}}^{r_y} \int_{m_{x-1}}^{m_x} P\{S_a(f) > s | m, r\} f_M(m) f_R(r) dm dr \right\}_i \quad (3.1)$$

- 2) Dividing the deaggregated hazard $\lambda_{s,x,y}$ for each m - r interval by the total hazard λ_s to determine the

relative contributions from different m - r intervals. A 3-dimensional histogram of relative contributions to hazard against coordinates m and r is constructed.

- 3) A representable earthquake, in terms of modal or mean values of m and r , is obtained. The modal earthquake (bi-variate modal value \hat{m} - \hat{r}) is the most-likely earthquake corresponding to the m - r interval having the largest contribution. The (marginal) mean earthquake is given by

$$\bar{m} = \sum_{x=1}^{x_N} \bar{m}_x \sum_{y=1}^{y_N} \frac{\lambda_{s,x,y}}{\lambda_s}, \quad (3.2)$$

$$\bar{r} = \sum_{y=1}^{y_N} \bar{r}_y \sum_{x=1}^{x_N} \frac{\lambda_{s,x,y}}{\lambda_s}, \quad (3.3)$$

where \bar{m}_x and \bar{r}_y are the central values of the associated m - and r -interval, respectively.

Comparatively, the modal earthquake would, more likely, represent a physically realizable earthquake. The mean earthquake is more capable of producing the expected hazard. In engineering practice, both scenario representations have been used.

It should be noted that

- a) In general, a SHD is performed towards a specific hazard s (or λ_s) at a specific frequency f . Hence, any summary statistics obtained refer to this condition.
- b) A single m - r pair is extracted in each SHD run. To obtain representative m - r pairs towards different s values, multiple SHD are performed separately.

3.2 SHD-based Single Earthquake Scenario

For specific engineering purposes, different SHD procedures have been proposed. McGuire (1995) proposed a deaggregation procedure to obtain a controlling event in terms of m , r , and ε , which induces hazard to match the target uniform hazard spectrum (UHS) in the frequency range of engineering interest. Deaggregation for ε requires the explicit integration with respect to ε in the standard PSHA formulation given in equation (2.1), where ε is modelled to follow the standard normal distribution and to be independent from m and r . Then ε can be deaggregated in a similar fashion as for m and r , using the following formula

$$\bar{\varepsilon} = \sum_{z=1}^{z_N} \bar{\varepsilon}_z \sum_{x=1}^{x_N} \sum_{y=1}^{y_N} \frac{\lambda_{s,x,y,z}}{\lambda_s}, \quad (3.4)$$

where ε_N is the total number of intervals divided for ε , $\bar{\varepsilon}_z$ is the central value of the associated ε -interval, and $\lambda_{s,x,y,z}$ is the hazard contribution by the associated m - r - ε interval.

In McGuire's procedure (1995), if one source dominates hazard at both 1.0 and 10 Hz, one controlling event, called β -earthquake ($m_\beta, r_\beta, \varepsilon_\beta$), is determined by taking the most-likely m_β , r_β , and ε_β . If two different sources dominate hazard at 1.0 and 10 Hz, two β -earthquakes are determined to represent hazard at 1.0 and 10 Hz, respectively. However, in both cases, ε_β is

manually adjusted to ensure that using the triplet m_β - r_β - ε_β and the GMPE the computed s recovers the target s , since there is no theoretical reason for that the as-deaggregated m_β - r_β - ε_β will replicate the target s (McGuire 1995).

Ni (2012) proposed the deaggregation in terms of the rate of occurrence v in addition to m and r to appreciate the role that v plays in the integrative PSHA. It is given by

$$\bar{v} = \sum_{i=1}^{N_s} v_i \frac{\lambda_s^i}{\lambda_s}, \quad (3.5)$$

where λ_s^i is the hazard contribution from source i . Using equations (3.2), (3.3), and (3.5), Ni (2012) determined a controlling earthquake (m_c, r_c, ε_c) at each of the eight selected frequencies, separately, to represent the dominant hazard at the respective frequencies and to approximate the UHS calculation. Reported errors in the approximations were within 20%.

Note that either McGuire's (1995) or Ni's (2012) SHD is to obtain a single earthquake scenario in each SHD run. The hazard representation using a single earthquake scenario has inherent limitations as discussed below.

Due to the integrative nature of a PSHA, no single event can fully represent the seismic threat to a site. In many practical cases, multiple m - r pairs show comparable contributions to a specific level of hazard. These m - r pairs typically generate ground motions significantly different in frequency content. As a result, a single m - r pair is inherently limited for representing seismic threat to the site. It is unlikely to find a single m - r pair that dominates hazard in the range of engineering interest (i.e., 1E-3~1E-6/yr) or across a frequency range of interest (e.g., 1~25 Hz). Hence, it is more appropriate to report different m - r pairs along with their relative contributions and make sure to reflect them properly in dynamic response analysis of engineering systems. However, little relevant research is found in the literature.

Following the existing SHD procedures, the earthquake scenario extracted may be very different as the reference probability level varies, especially for the low frequency hazard (e.g., 1 Hz). Hence, it is unlikely to extract a single earthquake scenario that induces dominant hazard to the site at all probability levels. In an effort to have a more complete understanding of the dominant earthquake threat to the site of nuclear generating stations in the U.S., the U.S. Nuclear Regulatory Commission (NRC) currently requires that multiple deaggregations be performed, whereby obtaining a single scenario earthquake (controlling earthquake) in each deaggregation run.

3.3 U.S. NRC Staff Position on Identifying Scenario Earthquakes

U.S. NRC (2007) issued regulatory guide, RG 1.208, to describe methods acceptable to NRC staff for use in implementing specific part of regulations. Regarding the deaggregation of mean hazard, the staff position is:

“Analysis of multiple ground motion levels are used to obtain a more complete understanding of the earthquake characteristics (i.e., mean magnitude and distances) that contribute to the high-frequency (5 and 10 Hz) and low frequency (1 and 2.5 Hz) hazard, than could be obtained from a single ground motion level (e.g., 1E-5/yr).”

Following this U.S. NRC staff position, Appendix D of RG 1.208 gives some detailed guidelines on performing the deaggregation:

- a. Perform a total of 12 SHD cases, using the ground motion levels corresponding to the 1E-4, 1E-5, and 1E-6 /yr mean hazard for spectral accelerations at 1, 2.5, 5, 20 Hz, respectively.
- b. Determine a total of 6 controlling earthquakes (m, r) based on the deaggregation results from 12 SHD cases, for high- and low-frequency, respectively, at 1E-4, 1E-5, and 1E-6/yr reference probability levels. The m and r at low (high) frequency are determined as the linear average of those for 1 and 2.5 Hz (5 and 10 Hz), respectively.

Note that a significant amount of work on SHD is required as shown in the NRC guidelines, which confirms the limitations of the current SHD procedures as identified in Section 1. Some work is still needed to improve the SHD procedure.

4 A SET OF SCENARIO EARTHQUAKES

This section presents a new SHD procedure to overcome the limitations in current SHD-based single earthquake scenario, which determines simultaneously a limited set of scenario earthquakes. These scenarios induce dominant hazard in the 1E-3~1E-6/yr probability range that matches the standard PSHA-based result.

PSHA integrates over the entire magnitude m - and distance r - domain. The effects of all potential earthquakes, from small near-field earthquakes to large far-field earthquakes, on the resulting ground motion intensities are considered. For engineering purposes, SHD is used for characterizing the relative contribution to hazard from all m - r intervals at a reference probability level. However, when a single scenario earthquake is extracted over the entire m and r domain, the complete picture of seismic threat is lost.

To better represent the earthquake threat to the site, it is necessary to include multiple scenario earthquakes in the deaggregation results with the expectation that these scenarios collectively induce the same hazard as that obtained from a standard PSHA in the primary probability range of interest, i.e., 1E-3~1E-6/yr.

4.1 A New Deaggregation Procedure

To include multiple scenario earthquakes in the deaggregation results, two primary technical aspects need to be addressed:

- 1) What m - r pairs to include?

- 2) How are the m - r pairs weighted?

In the proposed procedure, the representative m - r pairs to be included are obtained via the (M, R) -binning, i.e., dividing the integration domain in terms of m and r into a number of subdomains (M, R) -bins. Properly defined (M, R) -bin includes m - r pairs that generate similar ground motions, and thus can be referred to as a “characteristic” (M, R) -bin. For each characteristic (M, R) -bin, a single representative m - r pair is deaggregated “locally” using the following formulas

$$\bar{m}_i = \sum_{x=1}^{x_{Ni}} \bar{m}_x \sum_{y=1}^{y_{Ni}} \frac{\lambda_{s,x,y,(M-R)_i}}{\lambda_{s,(M-R)_i}}, \quad (4.1)$$

$$\bar{r}_i = \sum_{y=1}^{y_{Ni}} \bar{r}_y \sum_{x=1}^{x_{Ni}} \frac{\lambda_{s,x,y,(M-R)_i}}{\lambda_{s,(M-R)_i}}, \quad (4.2)$$

where $i=1 \dots N$ is the total number of characteristic (M, R) -bins. It is desirable to determine a minimum number of (M, R) -bins that could satisfactorily represent the m - r pair distribution in the seismic sources. Experience has shown that a number of 4 to 9 (M, R) -bins will typically satisfy this purpose. The m - r pair deaggregated using equations (4.1) and (4.2) represents the dominant event from the i^{th} (M, R) -bin.

With the representative m - r pairs determined locally within individual characteristic (M, R) -bins, the weight of each m - r pair is considered “globally” via the rate of occurrence v_i . Assuming that the weight of each representative m - r pair is related to the contribution to the overall hazard λ_s by its associated (M, R) -bin from all sources, the deaggregation of occurrence v_i is defined by

$$\bar{v}_i = \sum_{k=1}^{N_s} v_i \frac{\lambda_{s,k,(M-R)_i}}{\lambda_s}, \quad (4.3)$$

where $\lambda_{s,k,(M-R)_i}$ is the hazard contributed by the (M, R) -bin from source k .

In the above, for any specific ground motion level s , equations (4.1)-(4.2) provide a limited set of scenario earthquakes in terms of representative magnitude m_i and source-site distance r_i . Equation (4.3) provides the associated weight or rate of occurrence v_i ($i=1, \dots, N$). However, similar to any other existing SHD procedure, there is no theoretical reason to ensure that using the set of scenario earthquakes (m_i, r_i, v_i), where $i=1, \dots, N$, and the associated GMPEs, the target ground motion level s can be replicated.

For the purpose of approximating the hazard curve in the 1E-3~1E-6/yr probability range, the deaggregation needs to be performed in an iterative manner to ensure that the set of deaggregated scenario earthquakes provide satisfactory approximation to the accurate curve in the target range. The ground motion level s , towards which the deaggregation is performed, is to be adjusted to ensure good approximation. The approximation to PSHA is given by

$$\lambda_s \approx \sum_{i=1}^N v_i \cdot P\{S_a(f) > s | m_i, r_i\}, \quad (4.4)$$

where double integrations with respect to m and r from all sources is simplified by summation over N scenarios.

Having addressed the primary technical aspects, the proposed deaggregation procedure is summarized as follows and is shown in Figure 1:

1. Develop accurate mean hazard curve for the site using the standard PSHA procedure.
2. Determine a number of characteristic (M,R) -bins based on the seismic sources configuration, e.g., by 2×2 , 2×3 , or 3×3 partitions.
3. Deaggregate scenario earthquakes using equations (4.1)-(4.3) based on the (M,R) -binning.
4. Match the approximate hazard curve obtained using the scenario earthquakes and equation (4.4) to the standard curve in the $1E-3$ - $1E-6$ /yr probability range by adjusting s .

When a good approximation is ensured, the associated deaggregated scenario earthquakes become the final output of the proposed SHD procedure.

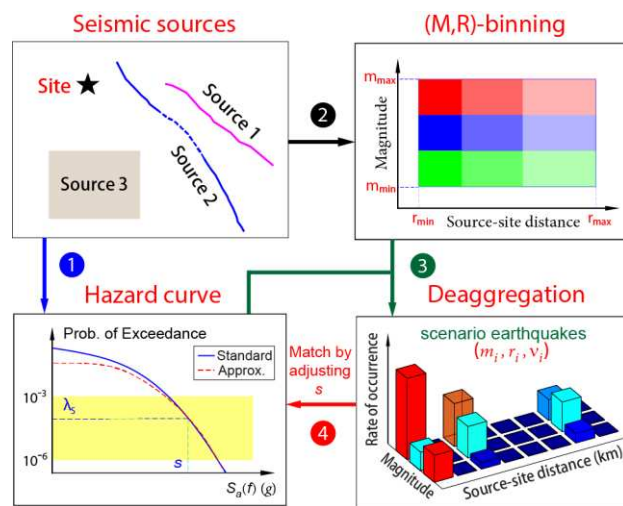


Figure 1: Proposed deaggregation procedure

The proposed deaggregation procedure is illustrated using a practical example in Section 5. Insights gained from the deaggregation results are discussed through the example.

5 NUMERICAL EXAMPLE

Site and model description

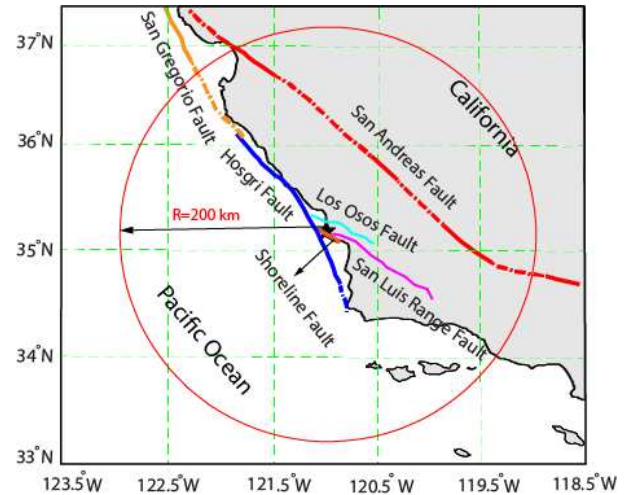


Figure 2: Seismic faults surrounding the Diablo Canyon Power Plant site

Take the site of Diablo Canyon power plant (DCPP) shown in Figure 2 as an example. The site is located at coastal California and has geodetic coordinates $[35.212^\circ \text{ N}, 120.854^\circ \text{ W}]$. There are four main near-field faults surrounding the site, i.e., Hosgri, Los Osos, San Luis Range, and Shoreline. The closest rupture distances of these faults to the DCPP site are approximately 7.0 km, 8.0 km, 2.5 km, and 0.6 km, respectively. It was shown that Hosgri fault dominates the seismic hazard at the DCPP site (PG&E 2011). The San Andreas and San Gregorio faults are far-field faults, having closest rupture distances of 77 km and 152 km, respectively. Only fault segments within a radial distance of $R=200$ km from the site are considered. All other secondary faults are neglected.

The probability distribution of source-site distance $f_R(r)$ for each fault is determined numerically from source configurations. The probability distribution $f_M(m)$ for each fault is taken from the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) model (USGS and CGS 2013), which includes both characteristic and Gutenberg-Richter earthquakes. A minimum moment magnitude $m_{\min}=5.0$ is used for all faults. The mean rate of occurrence ν for each fault is estimated using the original fault data, i.e., seismogenic area A and long-term slip rate \dot{u} (WGCEP 2003). All faults are taken as the strike-slip type for simplicity. The ground-motion prediction equations (GMPE) developed by Abrahamson and Silva (1997) are adopted to obtain the statistics for the conditional probability distribution of spectral accelerations for a given scenario earthquake. Note that newer versions of these GMPEs (Abrahamson and Silva 2008; Abrahamson *et al.* 2014) are not used to avoid introducing significantly more complexity in this example. Given a relatively high near-surface shear wave velocity ($\sim 1,200$ m/s) at this site (USNRC 2012), the site condition in the AS97 GMPE is set as generic rock.

Implementation of the proposed procedure

PSHA is performed in terms of spectral accelerations at 1, 5, and 10 Hz for the site. The resulting seismic hazard curves are shown in Figure 3.

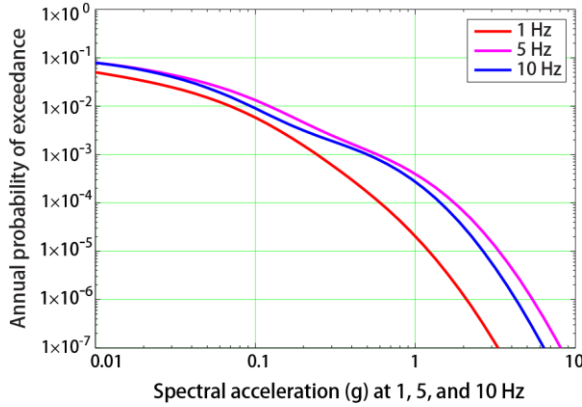


Figure 3: Seismic hazard curves for the DCPD site

Seen from Figure 2 of seismic source configurations, hazard at the DCPD site may be contributed by both near-field and far-field earthquakes. For low-frequency hazard, e.g., $S_a(1\text{Hz})$, the contribution of far-field earthquakes from San Andreas fault system can be significant. For high-frequency hazard, e.g., $S_a(10\text{Hz})$, near-field earthquakes would dominate the hazard. For high ground-motion intensity levels, near-field earthquakes tend to dominate hazard at both the low and high frequencies.

The (M,R) -binning using the 2×2 , 2×3 , or 3×3 partition schemes all have shown to produce excellent hazard approximations for this site application. Since it is desirable to use a minimum number of (M,R) -bins, only the 2×2 partition scheme is discussed in the following. The corresponding (M,R) -binning is given by:

$$M_S = [5.0, 6.8], \quad M_L = (6.8, 8.5];$$

$$R_S = [0, 10] \text{ km}, \quad R_L = (10, 200] \text{ km},$$

where the range of magnitude is bi-sectioned at $M6.8$ and the range of distance is partitioned at 10 km. Four characteristic (M,R) -bins are then obtained. Note that the partitions can be flexible, e.g., R-partition at 10~15 km produces equally good results. In addition, since the (>100 km) earthquakes contribute insignificantly to hazard, an upper bound R_L smaller than 200 km can be used, which often improves the approximation slightly.

Determination of scenario earthquakes is performed in an iterative manner by adjusting ground-motion level s value and using equations (4.1)-(4.4). Suppose that the $S_a(1\text{Hz})$ hazard is of current interest. Good approximation to $S_a(1\text{Hz})$ hazard is obtained at $s = 0.18 g$ and shown in Figure 4. The deaggregated scenario earthquakes are given in Table 1. For complete information, contribution to hazard from m - r pairs towards $s = 0.18 g$ is shown in Figure 5.

Table 1: Deaggregated scenario earthquakes

i	m_i	r_i	v_i
1	6.20	5.92	0.00063
2	6.42	31.87	0.00076
3	7.23	6.88	0.00043
4	7.61	88.55	0.01000

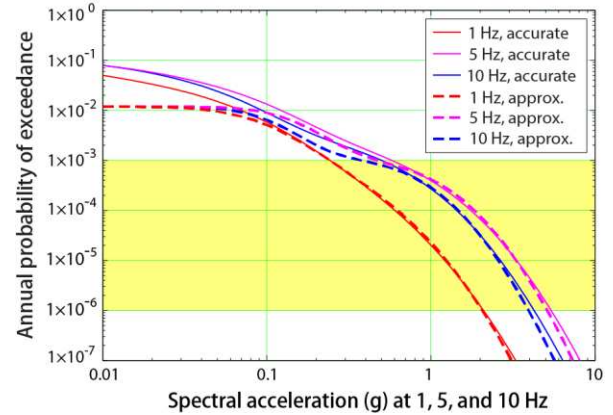


Figure 4: Hazard curve approximations using the set of scenario earthquakes given in Table 1

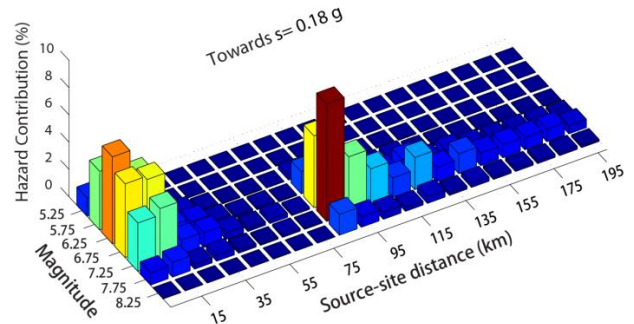


Figure 5: Contribution to $S_a(1\text{Hz})$ hazard towards $s=0.18g$

Advantages in hazard representation

The advantages of hazard representation using a set of scenario earthquakes given in Table 1 instead of a single scenario earthquake (found to be $m=6.82$, $r=11.00\text{km}$, and $v=0.0029$) are discussed below.

1. The set of scenario earthquakes collectively recover the $S_a(1\text{Hz})$ hazard curve obtained from standard PSHA in the $1\text{E}-3 \sim 1\text{E}-6/\text{yr}$ probability range as Figure 4 shows. The PSHA-consistent hazard induced by the set of scenarios validates their use in more engineering applications. In contrast, a single scenario cannot satisfactorily approximate the $S_a(1\text{Hz})$ hazard as shown in Figure 6.
2. Besides the $S_a(1\text{Hz})$ hazard, the set of scenario earthquakes can also satisfactorily approximate hazard in other frequencies. Figure 4 shows that the approximations to $S_a(5\text{ Hz})$ and $S_a(10\text{ Hz})$ hazard are also excellent in the $1\text{E}-3 \sim 1\text{E}-6/\text{yr}$ range. Another

way to showcase this advantage is to use the uniform hazard spectrum (UHS). Figure 7 shows both the approximate UHS obtained using the set of scenario earthquakes and the accurate UHS obtained from standard procedure, defined at three probability levels: $1E-5$, $1E-4$, and $4E-4$ /yr. All approximations are of high accuracy at the entire frequency range, with the maximum relative error less than 6%.

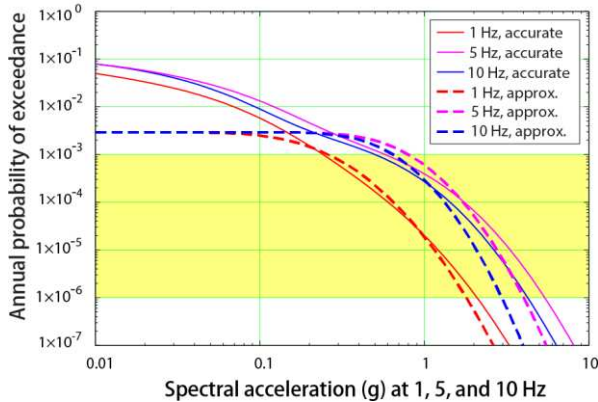


Figure 6: Hazard approximation using a single scenario earthquake ($m=6.82$, $r=11.00$ km, $v=0.0029$)

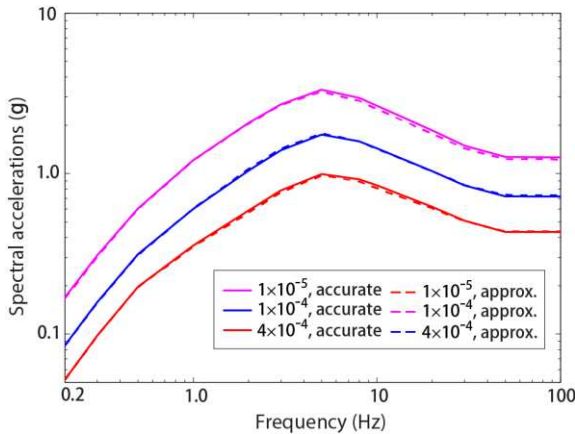


Figure 7: Uniform hazard spectra approximations using a set of scenario earthquakes

- The set of scenario earthquakes provide a more complete picture of the seismic threat to the DCPP site. As given in Table 1, scenario 1 represents small near-field event, scenario 2 represents small middle-field event, scenario 3 represents large near-field event, and scenario 4 represents large far-field event. The rate of occurrence v represents the weighting factor for each scenario to contribute to the overall hazard. These scenarios and rates of occurrence represent a wide spectrum of seismic events in a simplified manner compared to the thousands of earthquake occurrences considered in the original seismic sources. Information on different representative scenarios and the relative likelihoods of their occurrences is retained. In contrast, if a single

scenario earthquake is used, a lot of important information is simply lost.

However, it is noted that the rate of occurrence v does not represent the impact of each scenario on the overall hazard. The impact of earthquake scenarios on the overall hazard should be checked by the scenario deaggregation.

Figure 8 shows the scenario deaggregation for both the $S_a(1\text{ Hz})$ and $S_a(10\text{ Hz})$ hazard. It provides useful insights into the hazard threat at the DCPP site that a standard source deaggregation could not possibly provide:

- For both the $S_a(1\text{ Hz})$ and $S_a(10\text{ Hz})$ hazard, far-field earthquakes (scenarios 2 and 4) have insignificant impact on the overall hazard in the $1E-3\sim 1E-6$ /yr probability range.
- For the $S_a(1\text{ Hz})$ hazard, large near-field earthquake (scenario 3), even with the smallest rate of occurrence v_3 , has the most impact on the overall hazard in the $1E-3\sim 1E-6$ /yr range.
- For the $S_a(10\text{ Hz})$ hazard, near-field earthquakes (scenarios 1 and 3), even with small rates of occurrence, have more impact on the overall hazard. In addition, nearer-field earthquake (scenario 1) although smaller, tends to dominate hazard at very low probabilities.

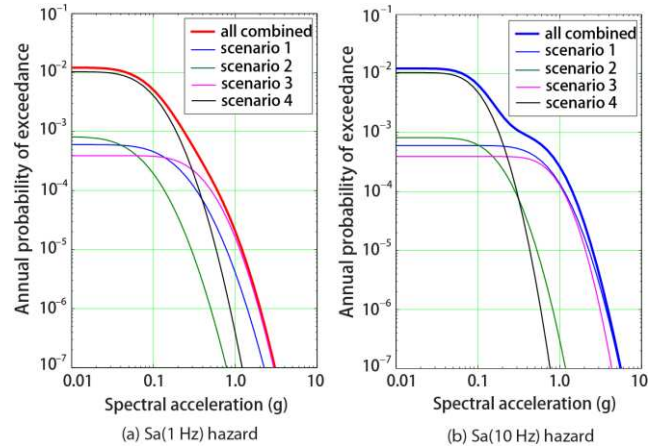


Figure 8: Contribution to hazard by scenarios

6 Conclusions

This paper presents a new seismic hazard deaggregation procedure that determines a set of scenario earthquakes in terms of magnitude m and source-site distance r . Earthquake weighting factor assigned to each scenario is defined in the form of the rate of occurrence v .

The set of scenario earthquakes deaggregated provide a better hazard representation than any single scenario. They can provide excellent approximations to hazard obtained by the standard PSHA procedure, at the $1E-3\sim 1E-6$ /yr probability range, for spectral accelerations at different frequencies.

A practical example is presented to illustrate the effectiveness of proposed deaggregation procedure. These scenarios provide useful insights into the most contributing events to hazard at the site.

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