Simulation-Based Seismic Hazard Assessment Using Monte-Carlo Earthquake Catalogs: Application to CyberShake

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ABSTRACT

The use of numerical simulations in probabilistic seismic hazard analysis (PSHA) has achieved a promising level of reliability in recent years. One example is the CyberShake project, which incorporates physics-based 3D ground-motion simulations within seismic hazard calculations. Nonetheless, considerable computational time and resources are required due to the significant processing requirements imposed by source-based models on one hand, and the large number of seismic sources and possible rupture variations on the other. This article proposes to use a less computationally demanding simulation-based PSHA framework for CyberShake. The framework can accurately represent the seismic hazard at a site, by only considering a subset of all the possible earthquake scenarios, based on a Monte-Carlo simulation procedure that generates earthquake catalogs having a specified duration. In this case, ground motions need only be simulated for the scenarios selected in the earthquake catalog, and hazard calculations are limited to this subset of scenarios. To validate the method and evaluate its accuracy in the CyberShake platform, the proposed framework is applied to three sites in southern California, and hazard calculations are performed for earthquake catalogs with different lengths. The resulting hazard curves are then benchmarked against those obtained by considering the entire set of earthquake scenarios and simulations, as done in CyberShake. Both approaches yield similar estimates of the hazard curves for elastic pseudospectral accelerations and inelastic demands, with errors that depend on the length of the Monte-Carlo catalog. With 200,000 yr catalogs, the errors are consistently smaller than 5% at the 2% probability of exceedance in 50 yr hazard level, using only ~3% of the entire set of simulations. Both approaches also produce similar disaggregation patterns. The results demonstrate the potential of the proposed approach in a simulation-based PSHA platform like CyberShake and as a ground-motion selection tool for seismic demand analyses.

KEY POINTS

- A Monte-Carlo catalog method is proposed to reduce the computational cost of CyberShake hazard calculations.
- A 200,000 yr catalog produces accurate hazard estimates with a significant reduction in computational cost.
- A faster development of simulation-based hazard maps can be achieved, given the reduced time-to-solution.

INTRODUCTION

The analysis and design of earthquake-resistant structures require an appropriate description of the level of shaking expected at the site, generally determined from a probabilistic seismic hazard analysis (PSHA). A typical PSHA framework requires an earthquake rupture forecast (ERF) that describes the relevant earthquake sources in a region of interest. For instance, the 2007 Working Group on California Earthquake Probabilities (WGCEP) characterizes the seismic sources in the California region through the Uniform California Earthquake Rupture Forecast Version 2 (UCERF2). This ERF contains time-dependent and time-independent models of the sources with magnitudes $M_w > 5$, and also accounts for background seismicity (Field *et al.*, 2009). The 2014 WGCEP later developed the Uniform California Earthquake Rupture Forecast Version 3 (UCERF3), which is the latest ERF for California to

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date (Field *et al.*, 2014). Compared to the previous version, UCERF3 includes a larger number of fault sections and accounts for multifault ruptures. In addition, PSHA requires a ground-motion model (GMM), such as ground-motion prediction equations (GMPEs), to determine the ground-motion intensity for the different scenarios. However, applying GMPEs in PSHA assumes ergodicity, that is, that the variability of ground motions across different sites and ruptures from past earthquakes represents the variability of ground motions at any site from any future earthquake. Anderson and Brune (1999) showed that the ergodic assumption can result in an overestimation of the hazard. In addition, the accuracy of GMPEs depends on the availability of data from historical earthquakes and is, hence, limited to scenarios with significant recorded evidence (Gregor *et al.*, 2014).

In the PSHA framework proposed by Cornell (1968) and further developed in McGuire (1995), the entire set of earthquake scenarios defined in the ERF is combined with the shaking levels estimated from the GMMs. This classical method for performing PSHA calculates the rates at which ground-motion levels are exceeded, considering all possible seismic sources. As an alternative method, early applications of Monte-Carlo simulations in PSHA (e.g., Rosenhauer, 1983) demonstrated how random sampling of seismicity could be used to develop synthetic earthquake catalogs for hazard calculations. In this case, rates of exceedance are calculated from only the earthquake scenarios sampled in the catalog. The Monte-Carlo method has been applied in, at least, three distinct approaches. The first approach consists of resampling an observed earthquake catalog to construct a long duration synthetic catalog (e.g., Ebel and Kafka, 1999). The second approach relies on existing earthquake catalogs to formulate a seismic source model (usually by defining uniform seismic source zones) and uses it to generate synthetic earthquake catalogs (e.g., Musson, 2000; Musson and Sargeant, 2007; Weatherill and Burton, 2010). The third approach, illustrated in more recent applications, uses established or predefined source models and GMMs to perform Monte-Carlo simulations (e.g., Assatourians and Atkinson, 2013; Bourne *et al.*, 2015; Lee *et al.*, 2018).

In recent years, numerical ground-motion simulation models have been employed, instead of GMPEs as GMMs, to cope with the limitations of GMPE-based PSHA (Convertito *et al.*, 2006; Graves *et al.*, 2011; Villani *et al.*, 2014). In this context, researchers at the Southern California Earthquake Center (SCEC) developed a methodology for performing PSHA in southern California (Graves *et al.*, 2011), using physics-based simulations. In this platform called CyberShake, ground-motion time series are simulated using seismic reciprocity for an ensemble of earthquake scenarios. In CyberShake study 15.12, which is the most recent published version for southern California (SCECpedia, 2015), these scenarios are obtained from UCERF2. For a complete kinematic description of the source, CyberShake then augments the rupture descriptions provided by UCERF2 with conditional hypocenter locations and slip distributions, using a slip-time history generator (Graves and Pitarka, 2014). Assigning multiple hypocenter locations and slip models to the same rupture accounts for the expected variability in the source parameters and the resulting simulated motions at a site and, hence, alleviates the need for the ergodic assumption (Graves *et al.*, 2011). Strain Green tensors (SGTs) are then calculated around the site of interest and postprocessed using seismic reciprocity to obtain the seismograms. The resulting numerical simulations incorporate physics related to the fault rupture, wave propagation in a 3D velocity model, and site response. These alternative GMMs are being increasingly utilized, as they allow the simulation of realistic ground motions for all arbitrary conditions, even for the less frequent and unobserved cases. In addition, site-specific responses such as directivity and sedimentary basin effects are naturally included, using a 3D velocity model. As a result, CyberShake simulations have received significant attention in recent studies focusing on validating and utilizing these simulations in engineering applications (Bijelić *et al.*, 2019; Chen and Baker, 2019; Fayaz *et al.*, 2020).

However, implementing the CyberShake approach in PSHA requires significant computational time and resources, partly imposed by the large number of rupture sources and variations needed for the development of hazard curves. Furthermore, the maximum frequency in the simulated time series depends on the spatial resolutions of the source and velocity models, which largely influence the computational demands. For example, CyberShake study 15.12 combines the deterministic low-frequency ground-motion time series obtained from the physics-based model with high-frequency stochastic seismograms generated using the SCEC broadband platform (Maechling *et al.*, 2015), at a transition frequency of 1 Hz (Jordan and Callaghan, 2018). The synthesis of the low-frequency component of the simulations at 336 sites utilized more than 30 million core-hours (Jordan and Callaghan, 2018). The SCEC research group is currently working on extending the deterministic calculations to shorter periods, by providing larger computational resources (Scott Callaghan, personal comm., 2020). The researchers are also working on altering the CyberShake workflow in a way that reduces its computational demands, for example, by eliminating the SGT extraction step applied in the previous workflow (Graves *et al.*, 2011). This elimination can reduce the amount of storage required and leads to better performance. On the other hand, additional computational resources are required to introduce UCERF3 to CyberShake, due to a larger number of faults compared to UCERF2. UCERF3 also requires configuring the stochastic slip-time history generator, which is currently unable to accommodate complex multifault rupture geometries. Alternatively, Milner *et al.* (2021) presented a fully deterministic PSHA framework that employs a physics-based earthquake simulator (RSQSim, Dieterich and Richards-Dinger, 2010) to efficiently

simulate earthquake sequences and full slip-time histories from the fault system developed in UCERF3. The RSQSim ruptures are then combined with the CyberShake ground-motion simulator. This RSQSim-CyberShake method overcomes the current limitations of stochastic slip-time history generators and captures some of the improvements of UCERF3 over UCERF2. Nonetheless, the generation of sufficiently long earthquake catalogs requires a considerable runtime, and further validation of RSQsim-CyberShake is warranted.

Although much research has been devoted to reducing the time-to-solution per site by modifying the CyberShake workflow, less attention has been paid to restricting the number of ground motions that need to be simulated per site. The purpose of this article is to present an efficient simulation-based PSHA framework that reduces the number of earthquake scenarios that need to be considered for the development of hazard curves at a site in CyberShake studies (and other studies that consider all the rupture sources from an empirical ERF). The capabilities of the proposed framework are demonstrated for CyberShake study 15.12 (hereafter simply referred to as CyberShake). The method corresponds to the third type of Monte-Carlo approaches in PSHA; it simulates synthetic earthquake catalogs with a specified duration by sampling earthquake scenarios from an empirical ERF (the mean hazard model of UCERF2 in the case of CyberShake). In this framework, ground motions are simulated only for the scenarios included in the catalog, and their corresponding intensity measures are then calculated and used to develop hazard curves. Limiting the number of numerical simulations shortens the time-to-solution per site currently required by CyberShake to develop hazard maps. The proposed method will address one of the main constraints of employing physics-based simulations, such as CyberShake in seismic hazard assessment, by making the analyses more practical among seismologists. Because of the flexibility of the Monte-Carlo method, the framework will allow a prompter update of the hazard maps whenever any of the ground motion, ERF, source, or velocity models is updated or improved.

For validation purposes, the proposed approach is illustrated at three sites in southern California, by developing Monte-Carlo catalogs with different lengths. The simulated ground motions that correspond to the scenarios selected in each catalog are then used to calculate the hazard curves at a range of spectral periods for each site. The accuracy of the proposed approach is evaluated based on the relative error between the hazard curves obtained from the Monte-Carlo catalogs and those obtained by considering the entire set of simulations. The latter represents the method that is used by CyberShake and provides a benchmark for evaluating the proposed approach. The variation of the accuracy of the hazard curves with the length of the Monte-Carlo catalog is then evaluated. Comparative analyses of postelastic seismic demands and disaggregation patterns are also performed as part of this study. Some preliminary results of the proposed approach were presented for a single site in Azar and Dabaghi (2020).

PROPOSED METHODOLOGY

This article presents a PSHA framework that employs numerically simulated ground motions, instead of conventional GMPEs, as GMMs. The framework is adapted to CyberShake and employs Monte-Carlo simulation to limit the number of ground-motion time series that need to be simulated to perform PSHA at a site. In the remainder of the article, the proposed approach is referred to as the Monte-Carlo catalog method; whereas, the approach that considers the entire set of simulations, which is currently used in CyberShake and described in Graves *et al.* (2011), is referred to as the full-fledged method. In the full-fledged method, the rates of exceedance needed to develop the hazard curves and perform hazard disaggregation at a site are obtained by considering all the scenarios that affect the site. These hazard curves and disaggregation results are treated as the reference or true results and are, hence, considered as a basis for comparison. Conversely, in the proposed Monte-Carlo catalog method, the exceedance rates and disaggregation results are determined by only considering the subset of the earthquake scenarios sampled by the catalogs generated using Monte-Carlo simulation. The Monte-Carlo catalog method is described in the following sections.

Seismic source model

Study 15.12 of CyberShake (Graves *et al.*, 2011; Jordan and Callaghan, 2018) uses the time-independent model of UCERF2 as a seismic source model and samples from a single branch that represents the mean hazard. UCERF2 provides the probability of occurrence of discretized fault ruptures in California that can generate earthquakes with $M_w > 5$ (Field *et al.*, 2009). Unlike UCERF2, CyberShake ignores background seismicity and only considers ruptures with $M_w > 6$ and that are within 200 km of a site of interest. Let I denote the number of these relevant ruptures for a given site. Moreover, CyberShake retains the magnitude estimates of the ruptures given by UCERF2 but adjusts the rupture areas using different magnitude–area scaling relations, to conform to the self-similar scaling of recorded ground motions (Graves *et al.*, 2011). For a complete description of the kinematic ruptures, CyberShake then transforms the ruptures into rupture variations by varying the hypocenter locations and slip distributions for the same rupture geometry. A uniform distribution is adopted for the location of the hypocenters, with a target spacing of 4.5 km. Given the location of a hypocenter on a fault, slip distributions are generated using the kinematic rupture generator of Graves and Pitarka (2014). This process results in an average of 415,000 scenarios to be considered at each site.

Earthquake catalog

In the proposed approach, synthetic earthquake catalogs are used to develop hazard curves at a site of interest. These catalogs are obtained by sampling a subset of all the possible earthquake scenarios using Monte-Carlo simulation. For a given site in the context of CyberShake, the I relevant ruptures and their k_i, $i = 1, \ldots, I$, associated rupture variations, as well as their probabilities are obtained from the seismic source model and are used to generate earthquake catalogs over a period of Y years. The number of rupture variations k_i represents the number of hypocenter locations and slip distributions assigned to rupture i. In CyberShake, the earthquakes from rupture i are assumed to follow a time-independent Poisson distribution. In this case, the mean annual rate of occurrence λ_i of each relevant rupture i is determined from its associated annual probability of occurrence P_i using

$$\lambda_i = -\log(1 - P_i). \tag{1}$$

The next step is to obtain N_i, the number of times a relevant rupture i occurs during the duration Y of the catalog, by random sampling from a Poisson distribution with a mean rate equal to $\lambda_i \times Y$. Each of the N_i occurrences of rupture i can have a different hypocenter location and slip distribution, that is, a different rupture variation. To determine the rupture variation of each of the $n_i = 1, \ldots, N_i$ occurrences, a random number is drawn with replacement from the probability distribution of the rupture variations. Because CyberShake assumes equiprobability of the k_i rupture variations of the same rupture i, a uniform distribution ranging from 1 to k_i is used in this study. The same procedure is applied to determine the N_i earthquake scenarios caused by the ith rupture for all the I relevant ruptures. The result is a simulated catalog that contains $\sum_i N_i$ earthquake scenarios, which are considered as one possible realization of the seismic events that may affect the site over a duration of Y years. Naturally, as the duration Y of the catalog increases, more seismic events are expected to occur, and the number of earthquake scenarios $\sum_i N_i$ increases.

Seismic hazard curves

After an earthquake catalog with a duration of Y years is developed, ground-motion time series are simulated at the site of interest exclusively for the earthquake scenarios sampled in the catalog. The result is a set of ground motions that may affect the site in Y years. Hazard curves for the site can then be developed for any intensity measure that can be calculated from the ground-motion time series. For a certain intensity measure IM, the mean annual rate of exceedance λ_α of an intensity threshold α is calculated in the manner of Ebel and Kafka (1999) using

$$\lambda_\alpha = \lambda(\mathrm{IM} > \alpha) = \frac{1}{Y}\sum_{i=1}^{I}\sum_{n=1}^{N_i} H[\mathrm{IM}_{i,n} - \alpha], \tag{2}$$

in which $\mathrm{IM}_{i,n}$ is the intensity measure of the ground motion corresponding to the nth occurrence of the ith rupture in the simulated catalog, and $H[\cdot]$ is the Heaviside function.

The hazard curves are obtained by plotting λ_α against different thresholds α of the intensity measure. As shown in equation (2), the hazard calculations only involve the ground motions of the sampled earthquake scenarios, in contrast with the full-fledged method in which λ_α is obtained by considering all the ruptures and ruptures variations affecting a site using

$$\lambda_\alpha = \lambda(\mathrm{IM} > \alpha) = \sum_{i=1}^{I}\left[\frac{\lambda_i}{k_i}\sum_{j=1}^{k_i} H[\mathrm{IM}_{i,j} - \alpha]\right], \tag{3}$$

in which $\mathrm{IM}_{i,j}$ is the intensity measure of the ground motion for the jth rupture variation of the ith rupture.

The proposed methodology can also be used to develop the seismic demand hazard curves of a structure for any response variable (or engineering demand parameter) and at any site of interest. In this case, dynamic analyses of the selected structure are performed exclusively for the ground motions of the scenarios sampled in the Monte-Carlo catalog simulated for the site. The structural responses calculated for this subset of scenarios are then used to compute the seismic demand hazard curve of the structure in accordance with equation (2), by replacing the IM by the specified demand parameter. Similarly, the reference or true demand hazard curve, corresponding to the full-fledged method, is obtained from equation (3) by replacing the IM by the specified demand parameter. The proposed methodology can be adapted to time-dependent earthquake-probability models, nonuniform distributions of the rupture variations, and any physics-based or site-based ground-motion simulation method.

CASE STUDY

A case study is used to illustrate and validate the proposed methodology and to evaluate the effect of the length Y of the Monte-Carlo catalog on the accuracy of the resulting hazard curves. This will help to select an optimal catalog length that reduces the computational time for performing simulation-based PSHA in CyberShake while still maintaining acceptable levels of accuracy. The procedure described in the previous paragraph is used to generate multiple synthetic earthquake catalogs at three different sites and for various values of Y. The resulting hazard curves are compared with the outputs from the full-fledged method. Because both the full-fledged and the Monte-Carlo catalog methods use the same seismic source model and GMM, this comparison allows evaluating the effect of catalog length on the computed rates and the accuracy of the proposed approach.

Three sites located in the Los Angeles region are selected from the CyberShake database and used in this case study. The first site is a basin site located in Los Angeles downtown (LADT). The second site is located in Pasadena (PAS), outside

TABLE 1
Characteristics and Number of Ruptures and Earthquake Scenarios of the CyberShake Sites Considered in This Study

Site	Latitude (°)	Longitude (°)	V_{S30}(m/s)*	$Z_{2.5}$ (km)*	Number of Ruptures	Number of Earthquake Scenarios
LADT	34.05204	−118.25713	365.4	2.08	7,019	476,920
PAS	34.14843	−118.17119	838.8	0.31	7,155	484,943
SBSM	34.06499	−117.29201	357.1	1.77	7,044	483,672

*Measures are calculated from the Community Velocity Model (CVM-S4.26; Chen and Lee, 2015). LADT, Los Angeles downtown; PAS, Pasadena; SBSM, San Bernardino strong motion.

TABLE 2
Mean Number of Ruptures and Earthquake Scenarios in the Simulated Catalogs at LADT, PAS, and SBSM and the Percent Reduction Compared to the Full-Fledged Method

			Catalog Duration (Yr)						
Site	Number of	Mean or Percent Reduction	10,000	20,000	50,000	100,000	200,000	500,000	1,000,000
LADT	Ruptures	Mean (% reduction)	644 (91)	1,025 (85)	1,773 (75)	2,464 (65)	3,379 (52)	4,708 (33)	5,699 (19)
	Earthquake scenarios	Mean (% reduction)	1,012 (100)	1,958 (100)	4,564 (99)	8,455 (98)	15,065 (97)	30,433 (94)	49,096 (90)
PAS	Ruptures	Mean (% reduction)	655 (91)	1,036 (86)	1,767 (75)	2,502 (65)	3,412 (52)	4,809 (33)	5,794 (19)
	Earthquake scenarios	Mean (% reduction)	1,017 (100)	1,999 (100)	4,597 (99)	8,562 (98)	15,118 (97)	30,792 (94)	49,669 (90)
SBSM	Ruptures	Mean (% reduction)	660 (91)	1,026 (85)	1,729 (75)	2,425 (66)	3,324 (53)	4,684 (34)	5,707 (19)
	Earthquake scenarios	Mean (% reduction)	1,089 (100)	2,119 (100)	4,931 (99)	8,917 (98)	15,533 (97)	30,494 (94)	48,496 (90)

LADT, Los Angeles downtown; PAS, Pasadena; SBSM, San Bernardino strong motion.

the Los Angeles basin. The third site, San Bernardino strong motion (SBSM), is subject to the coupling of basin and directivity effects. These three locations are selected to evaluate whether basin and directivity effects have any effect on the accuracy of the proposed methodology. The coordinates, basin depths (depth to the 2.5 km/s shear-wave velocity $Z_{2.5}$), and soil conditions (30 m averaged shear-wave velocity V_{S30}) at these sites are provided in Table 1. The ensemble of seismic ruptures located within 200 km from each site is extracted from the CyberShake database, with their associated annual probabilities of occurrence. In addition, the full set of corresponding earthquake scenarios at the three sites are identified and extracted from the database. The numbers of ruptures and earthquake scenarios identified for each site are also listed in Table 1.

Earthquake catalogs

Earthquake catalogs are developed for the three selected sites, as described in the Proposed Methodology section. First, 10 Monte-Carlo catalogs having a duration of 10,000 yr are generated at each site. Multiple catalogs are simulated for the same catalog duration, to account for the variability in Monte-Carlo simulations. For example at LADT, the 10 catalogs of 10,000 yr contain an average of 644 ruptures and 1012 earthquake scenarios, as mentioned in Table 2. Next, synthetic ground-motion time series should be simulated to represent each earthquake scenario in the 10 catalogs of each site. However, members from the SCEC research group provided the numerical simulations from CyberShake study 15.12 for the entire set of earthquake scenarios corresponding to the sites that were used in this study. Therefore, the synthetic ground motions for the scenarios sampled in the earthquake catalogs are selected (instead of being simulated) from the collection of all the synthetic ground motions already generated by SCEC for LADT, PAS, and SBSM. The RotD50$S_a(T)$ pseudospectral acceleration values (Boore, 2010), hereafter simply denoted as $S_a(T)$, of the selected synthetic ground motions are then calculated at periods $T = 0.1$, 0.2, 0.5, 1, 2, and 5 s for a fixed viscous damping ratio of 5%. Then, for each site and at each period, hazard curves that correspond to each simulated catalog are calculated, as described in the Proposed Methodology section.

To evaluate the effect of the duration Y of the catalog, additional catalogs are simulated at the three sites, using the same method applied to the 10,000 yr catalog. In total, 10 earthquake

catalogs are generated at each of LADT, PAS, and SBSM and for each of the following durations: 10,000; 20,000; 50,000; 100,000; 200,000; 500,000; and 1,000,000 yr. The mean number of ruptures and earthquake scenarios across the 10 catalogs for the different catalog lengths are summarized in Table 2 for the three sites. As expected, the number of earthquake scenarios increases with catalog length, because more earthquake events are expected to occur over a longer time. In the full-fledged method, the complete set of ruptures and earthquake scenarios is considered, which requires the simulation of a ground motion for each earthquake scenario. For instance, and as mentioned in Table 1, the source model identifies 7019 significant ruptures that are located within 200 km of LADT, and CyberShake defines 476,920 corresponding earthquake scenarios. Table 2 shows that, using the Monte-Carlo catalog method, the number of ground motions that need to be simulated (and stored) at LADT decreases. The average reduction in the number of ruptures depends on the length of the catalogs and varies from 19% for the 1,000,000 yr catalogs to 91% for the 10,000 yr catalogs. Similarly, the number of earthquake scenarios required in the 1,000,000 yr catalogs is 90% less than what is required by the full-fledged method and is almost 100% less for the 10,000 yr catalogs. Similar reductions in the number of ruptures and earthquake scenarios are also observed at PAS and SBSM, as indicated in Table 2.

Computational demands

In the CyberShake workflow, once the velocity mesh is generated, seismograms at a site are computed through a computationally demanding two-step process. The first step involves calculating the SGTs for all the faults of interest via reciprocity, using an anelastic finite-difference wave propagation algorithm. Postprocessing is performed as a second step to generate a seismogram for each rupture variation through a convolution of the corresponding SGTs and the slip time history at each point along the surface of the rupture. The full-fledged method, which is used to develop hazard curves in CyberShake, entails a large number of numerical simulations per site obtained via the described process and, thus, requires intensive computational time and resources (Graves *et al.*, 2011). In a more recent CyberShake workflow, both steps are almost equally demanding (Scott Callaghan, personal comm., 2020). The performance in the first step of the process depends on the size of the volume that covers the fault surfaces of all the ruptures located within 200 km from the site and for which SGTs need to be computed. This volume is, however, not significantly reduced in the Monte-Carlo catalog method, despite the reduction in the number of ruptures, because multiple ruptures in the CyberShake source model share common surface geometries, and, hence, most of the fault surfaces will still be included in the volume (Scott Callaghan, personal comm., 2020). Therefore, the proposed approach has a low impact on the computational cost of the SGT calculation step. However, the runtime of the postprocessing step scales with the product of the number of timesteps and the number of rupture surface points involved in the convolution process. Consequently, the postprocessing job is significantly less computationally demanding, if the number of earthquake scenarios is reduced. At LADT, and using a 200,000 yr catalog, the number of points on the surface of ruptures that need to be considered in the convolution is, approximately, 0.72% of the total number of points considered in the full-fledged method. Similar reductions apply to PAS and SBSM for the same catalog duration. This represents a major reduction (more than 99%) in the computational cost of the postprocessing step. Hence, the time-to-solution per site required by CyberShake is shortened significantly, by simulating a shorter catalog. Nonetheless, the choice of the optimal catalog length also depends on the desired accuracy of the resulting hazard curves.

Hazard curves

$S_a(T)$ hazard curves corresponding to the different simulated catalogs are computed at periods $T = 0.1$, 0.2, 0.5, 1, 2, and 5 s, for a fixed viscous damping ratio of 5%. Figure 1 shows the $S_a(T)$ hazard curves at LADT for a period $T = 2$ s developed using 10 different Monte-Carlo catalogs having the same length Y for $Y = 10{,}000$ yr, $Y = 100{,}000$ yr, $Y = 500{,}000$ yr, and $Y = 1{,}000{,}000$ yr. The computed hazard curves are compared at the same site and period with results from the full-fledged method. Figure 1 also indicates the most commonly used hazard levels that correspond to a 2%, 5%, and 10% probability of exceedance (PE) in 50 yr. Figure 1a shows that for $Y = 10{,}000$ yr, the hazard curves from the different catalog realizations are variable and diverge from the full-fledged hazard curve, especially at higher hazard levels. Thus, the number of scenarios in a 10,000 yr earthquake catalog does not seem sufficient to represent the higher hazard levels. In fact, as the ground-motion intensity threshold ($S_a(T)$ in this study) increases, the number of ground motions with intensity above the threshold decreases, resulting in less accurate rates at higher hazard levels. However, as can be observed in Figure 1b–d, when the length Y of the catalog increases, the variability in the hazard curves from the different Monte-Carlo catalogs is less pronounced, and the curves become closer to the curve from the full-fledged method even at the higher hazard levels. Figure 2 illustrates hazard curves developed at LADT, PAS, and SBSM using 200,000 yr catalogs for different periods. Figure 2a,b indicates that, at the same site, the methodology is accurate for both short and long periods. On the other hand, as pointed out by Figure 2b–d, the proposed methodology is not site-dependent because the variabilities in the hazard curves are comparable between the sites. In addition, Figures 1b,c, and 2 show that the hazard curves computed from catalogs with a duration of 200,000 yr or longer are good representations of the full-fledged method hazard curves, at the commonly used hazard levels.

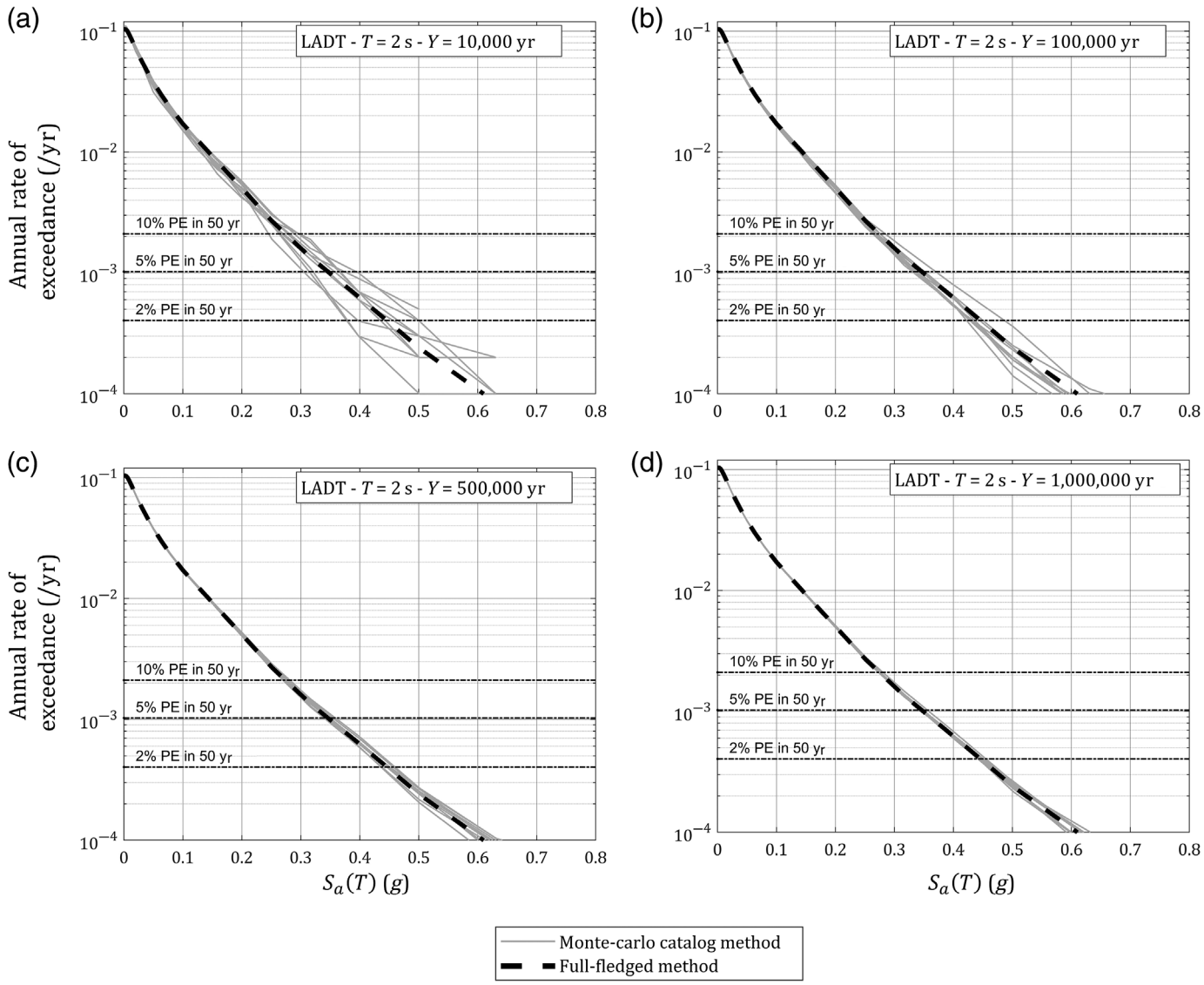

Figure 1. Comparison at Los Angeles downtown (LADT) of $S_a(T = 2\ \text{s})$ hazard curve from the full-fledged method with hazard curves developed from Monte-Carlo catalogs with (a) $Y = 10{,}000$ yr, (b) $Y = 100{,}000$ yr, (c) $Y = 500{,}000$ yr, and (d) $Y = 1{,}000{,}000$ yr. PE, probability of exceedance.

To quantify the accuracy of the computed hazard curves, relative errors on $S_a(T)$ at the frequently used hazard levels are calculated as in equation (4), in which $S_{a,\text{MC}}(T;\lambda)$ and $S_{a,\text{FF}}(T;\lambda)$ are the spectral accelerations at the same hazard level (or mean annual rate of exceedance λ) from the hazard curves for period T obtained from the Monte-Carlo catalog and full-fledged methods, respectively:

$$\text{Relative error}(\%) = \frac{S_{a,\text{MC}}(T;\lambda) - S_{a,\text{FF}}(T;\lambda)}{S_{a,\text{FF}}(T;\lambda)} \times 100. \qquad (4)$$

These values measure the difference in the hazard estimates between using the subset of scenarios sampled in a Monte-Carlo catalog on one hand and considering all the scenarios on the other. The errors are calculated for each computed hazard curve at the different periods and hazard levels. Figure 3 represents the boxplots of these errors at the 5% PE in 50 yr hazard level for different catalog durations at LADT, PAS, and SBSM. Each boxplot shows summary statistics of the relative errors obtained from the six different periods and 10 sets of catalogs for the specified site, hazard level, and catalog duration (60 data points in each boxplot). The statistics include, in order, the minimum, first quartile, median, third quartile, and maximum values, excluding any outliers. The figure shows that the median error values for the different catalog lengths are generally close to zero. This observation implies that the results from the Monte-Carlo catalog method are unbiased and that the proposed approach is functional in the CyberShake platform. On the other hand, Figure 3 highlights the significant effect of catalog length on the variability and accuracy of the resulting hazard curves. Although the relative error can reach 17% with a 10,000 yr earthquake catalog, it is

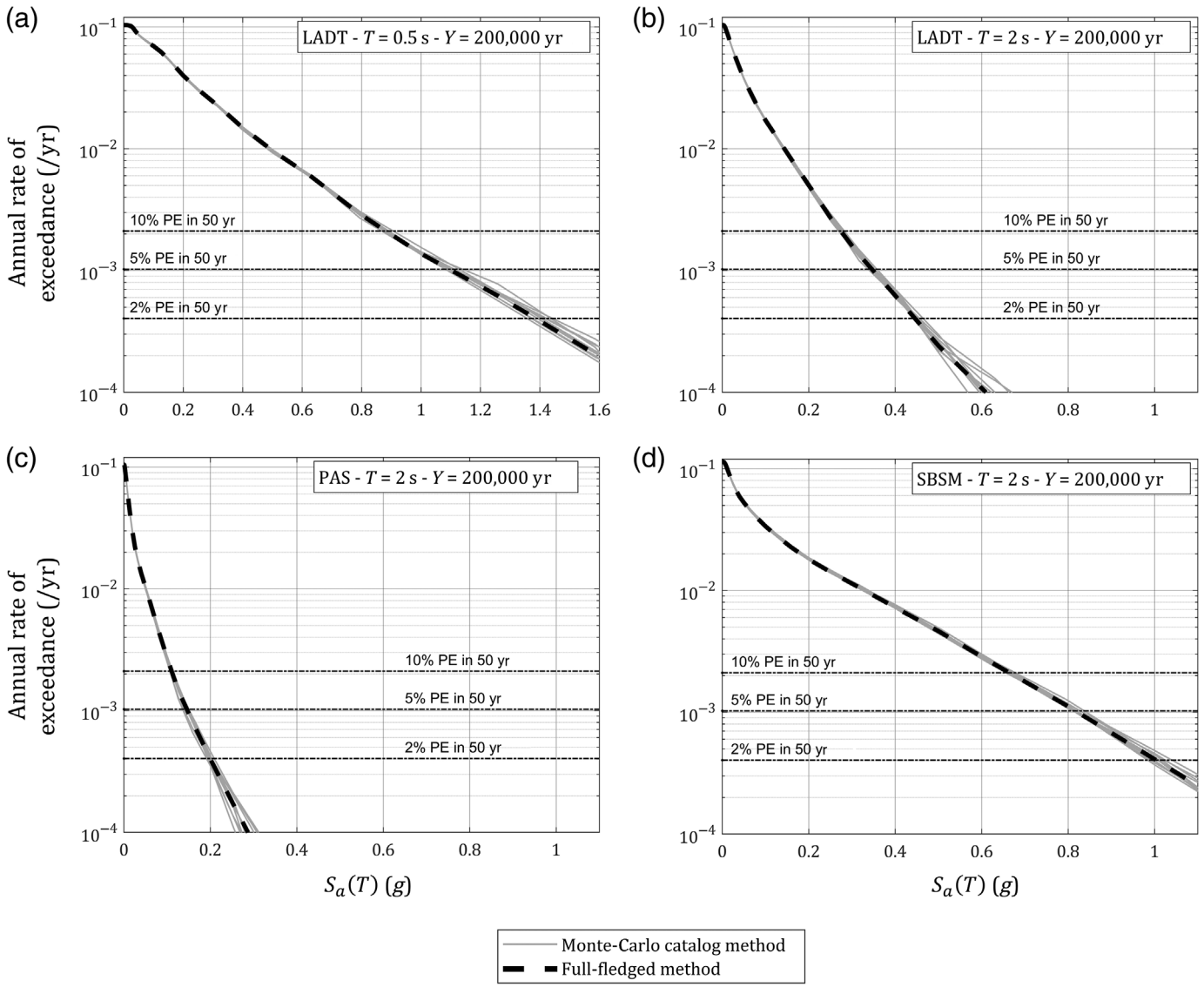

Figure 2. Comparison of $S_a(T)$ hazard curves from the full-fledged method with hazard curves developed from Monte-Carlo catalogs with $Y = 200{,}000$ yr (a) LADT for $T = 0.5$ s, (b) LADT for $T = 2$ s, (c) PAS for $T = 2$ s, and (d) SBSM for $T = 2$ s. LADT, Los Angeles downtown; PAS, Pasadena; PE, probability of exceedance; SBSM, San Bernardino strong motion.

reduced to less than 4% when using a 200,000 yr catalog and less than 2% with a 1,000,000 yr catalog. The absolute values of the relative errors from equation (4) are also calculated. For LADT, the median of the absolute relative error from the 200,000 yr catalog at the 2% PE in 50 yr hazard level is 1.3% across the six different periods and 10 sets of catalogs, with a 95th percentile of 4.5%. Similar ranges of absolute relative errors are observed at the other sites for the same catalog duration and hazard level.

These results underline the expected trade-off that exists between the length of the catalog and the accuracy of the computed hazard estimates: a longer catalog results in more accurate hazard curves whereas a shorter catalog requires less computational resources. The selection of the optimal catalog length should balance between these two aspects. For the hazard levels of common engineering interest, the 200,000 yr catalog can be considered suitable to implement Monte-Carlo catalogs in a simulation-based PSHA. It reduces the number of earthquake scenarios at the sites considered in this study by more than 97% compared to the full-fledged method while still maintaining acceptable relative errors.

Seismic demand hazard curves are also developed as a part of this study at the LADT site. For this purpose, a nonlinear degrading single-degree-of-freedom (SDoF) system is considered to act as a proxy for a more complex multi-degree-of-freedom (MDoF) system. The SDoF system used has an initial period of $T = 2$ s with a force-deformation response similar to the ones used by Bradley *et al.* (2015) and Burks and Baker (2014). The hysteretic backbone relationship of the SDoF is illustrated in Figure 4, and its unloading and reloading behavior is represented by the peak-oriented model defined by Ibarra *et al.* (2005) with negligible cyclic deterioration.

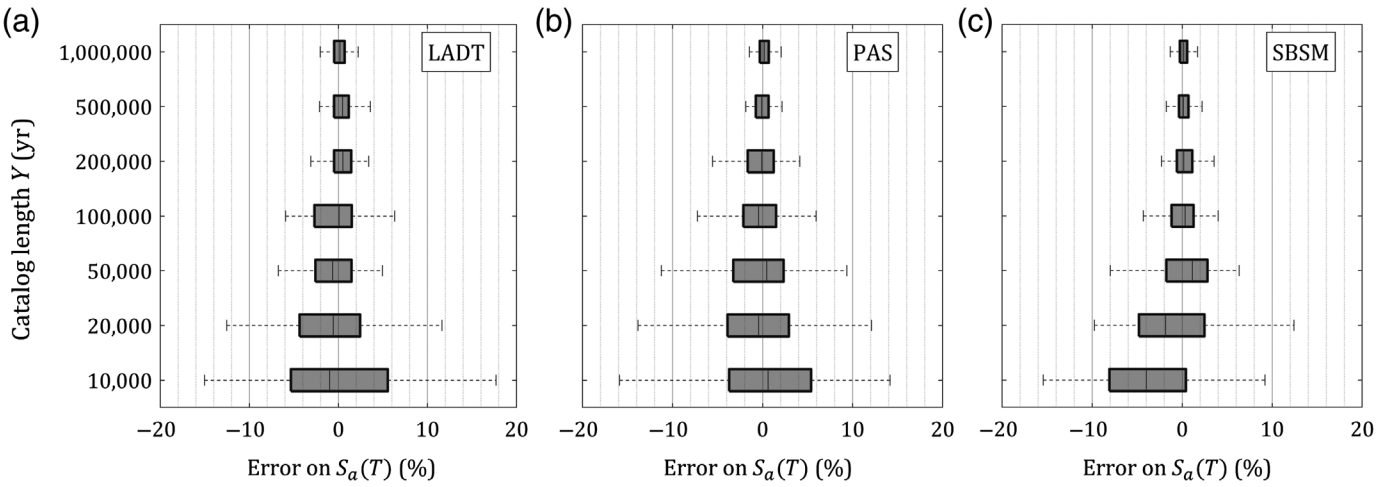

Figure 3. Boxplots of relative errors on $S_a(T)$ between the Monte-Carlo catalog method and the full-fledged method at the 5% PE in 50 yr hazard level at (a) LADT, (b) PAS, and (c) SBSM.

In the context of demand hazard curves, the full-fledged method requires running around 415,000 nonlinear response history analyses per SDoF system using the CyberShake seismograms simulated at LADT. The curve obtained using this large set of ground motions constitutes a robust benchmark for comparison with the proposed approach. The dynamic analyses were performed in OpenSees (McKenna *et al.*, 2010). Seismic demand hazard curves in terms of the peak displacement of the SDoF system are developed using both the full-fledged method and the proposed approach. In the latter, the Monte-Carlo catalogs previously developed for LADT are used. Figure 5a displays the seismic demand hazard curves of the 2 s nonlinear SDoF at LADT obtained from the full-fledged method and the 10 Monte-Carlo catalogs with $Y = 200{,}000$ yr. Similar to Figure 2a, the hazard curves from the 10 catalogs are comparable to the hazard curve from the full-fledged method at the 2%, 5%, and 10% PE in 50 yr hazard levels, and their variability is negligible. This small variability indicates that the seismic demand hazard curves developed using a 200,000 yr catalog are consistent. Relative errors between the demand curves of the two approaches are calculated using equation (4) adapted to the seismic demand analysis by replacing $S_a(T)$ by the peak displacement. The range of relative errors on the demand curve of Figure 5a at the 5% PE in 50 yr hazard level is presented in Figure 5b, along with the relative errors from the other Monte-Carlo catalog durations at the same hazard level. As expected, the relative error on the peak displacement decreases as the catalog duration increases, and drops below 2% for $Y \geq 200{,}000$ yr. The results thus show promise in the ability of the proposed approach to be extended to the development of seismic demand hazard curves for nonlinear structures using numerical simulations. Nonetheless, further exploration is required by considering more complex MDoF systems. In this case, the Monte-Carlo approach can be used as a ground-motion selection tool for performance-based design. The tool alleviates the need to perform dynamic analyses for the entire set of numerical simulations (such as in Bijelić *et al.*, 2019) and still results in accurate seismic demand hazard curves.

Hazard disaggregation

To further validate the proposed method, a disaggregation of the magnitude M_w and the closest source-to-site distance R_{rup} of the contributing scenarios is applied to the full-fledged method and one of the 10 simulated 200,000 yr catalogs at PAS at the different periods and hazard levels. Figure 6 represents the $M_w - R_{rup}$ disaggregation at the 5% PE in 50 yr hazard level for $S_a(T)$ at $T = 0.5$ s and $T = 5$ s. The left and right

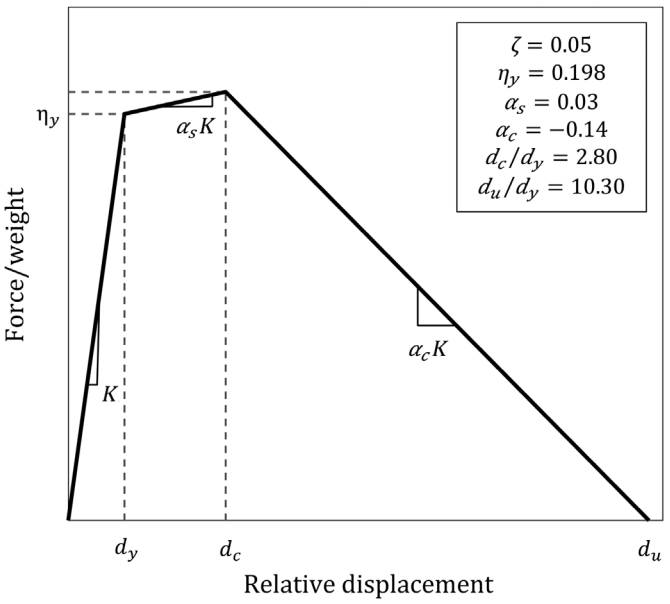

Figure 4. Hysteretic backbone curve of the inelastic single-degree-of-freedom (SDoF) system considered, in which η_y is the ratio between the yield force and the weight of the system, K is the elastic stiffness, α_s is the hardening stiffness ratio, α_c is the postcapping stiffness ratio, d_y is the yield displacement, d_c is the cap displacement, and d_u is the ultimate displacement.

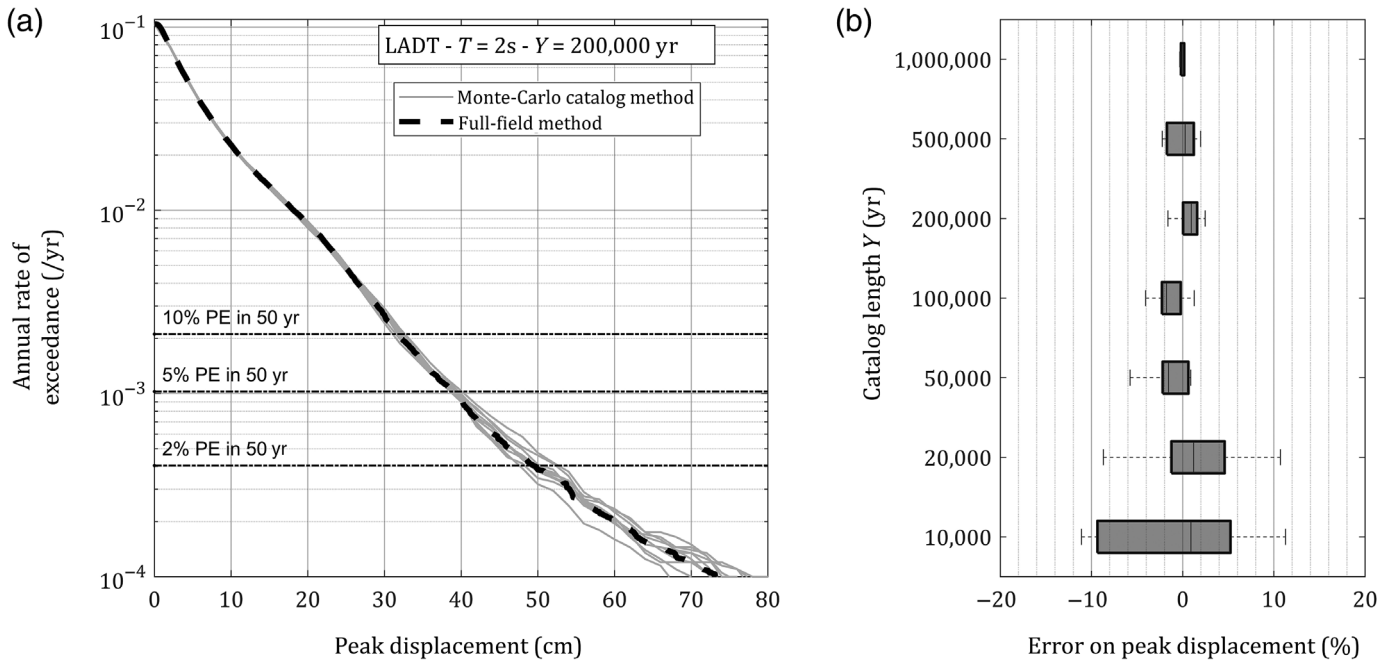

Figure 5. (a) Comparison of the seismic demand hazard curve of the 2 s nonlinear SDoF system at LADT from the full-fledged method with curves developed from Monte-Carlo catalogs with $Y = 200{,}000$ yr; and (b) boxplots of relative errors on the peak displacements at the 5% PE in 50 yr hazard level.

plots correspond to the disaggregation from the full-fledged and Monte-Carlo methods, respectively. It can be observed from Figure 6a (left) that the seismic hazard at PAS at $T = 0.5$ s is mostly controlled by earthquake scenarios with M_w between 6.25 and 7.25 at short distances ($R_{rup} \leq 10$ km). A similar disaggregation pattern is observed for the 200,000 yr catalog shown in Figure 6a (right). The only difference is that some of the least contributing scenarios (e.g., $7.25 \leq M_w \leq 8.25$ and $R_{rup} \geq 20$ km) do not appear when the 200,000 yr catalog is used.

The $M_w - R_{rup}$ disaggregation patterns of the two methods are also similar at $T = 5$ s, as illustrated in Figure 6b. At longer periods, earthquakes from larger distances contribute to the hazard. The first mode of the disaggregation from both methods is characterized by R_{rup} between 40 and 50 km and a mean M_w equal to 8. Scenarios with M_w between 6.75 and 7.25 and $R_{rup} <$ 10 km also contribute to the hazard and with similar proportions from both methods. Furthermore, a contribution from scenarios with $R_{rup} \geq 50$ km is observed in both histograms. Nonetheless, the least contributing $M_w - R_{rup}$ bins are not all captured by the Monte-Carlo approach, which is explained by the reduced number of scenarios in the synthetic earthquake catalogs.

Figure 7 illustrates the source disaggregation at the 5% PE in 50 yr hazard level at PAS obtained using both approaches at $T = 0.5$ s and $T = 2$ s. The left and right plots correspond to the disaggregation from the full-fledged and Monte-Carlo methods, respectively. At $T = 0.5$ s, the contributing sources from the 200,000 yr Monte-Carlo catalog and their contribution proportions are close to the results from the full-fledged method. For instance, both plots in Figure 7a show that the most contributing fault is the upper segment of the Elysian Park fault, followed by the Verdugo and Raymond faults. For the longer period $T = 2$ s, a larger number of faults contribute to the hazard, including more distant faults. The results from both methods are consistent for the three most contributing sources as seen in Figure 7b. As the contribution proportion decreases, some differences are observed between the two methods, such as the case of the Sierra Madre fault and the upper segment of the Elysian Park fault. These minor differences are expected because the Monte-Carlo catalog method does not consider all the earthquake scenarios.

The $M_w - R_{rup}$ and source disaggregation patterns for PAS at the 5% PE in 50 yr (at both short and long periods) obtained using a 200,000 yr Monte-Carlo catalog are mostly similar to the patterns obtained using the complete set of scenarios. Consistency of the disaggregation patterns is also observed for the other periods and hazard levels of common engineering interest, and at the LADT and SBSM sites. This similarity between the two methods is an additional key validation of the proposed Monte-Carlo catalog method.

The proposed methodology is also tested at a site from CyberShake study 18.8, located in northern California (SCECpedia, 2018) to explore the relevance of the proposed approach in other geographic regions. The site Sutter Buttes (SUTB) is selected for the verification. In contrast to sites in the Los Angeles region, SUTB is exposed to lower levels of seismic hazard and is mainly affected by faults with low slip rates and located at distances greater than 40 km. The Monte-Carlo approach yields ranges of errors in the hazard calculations and

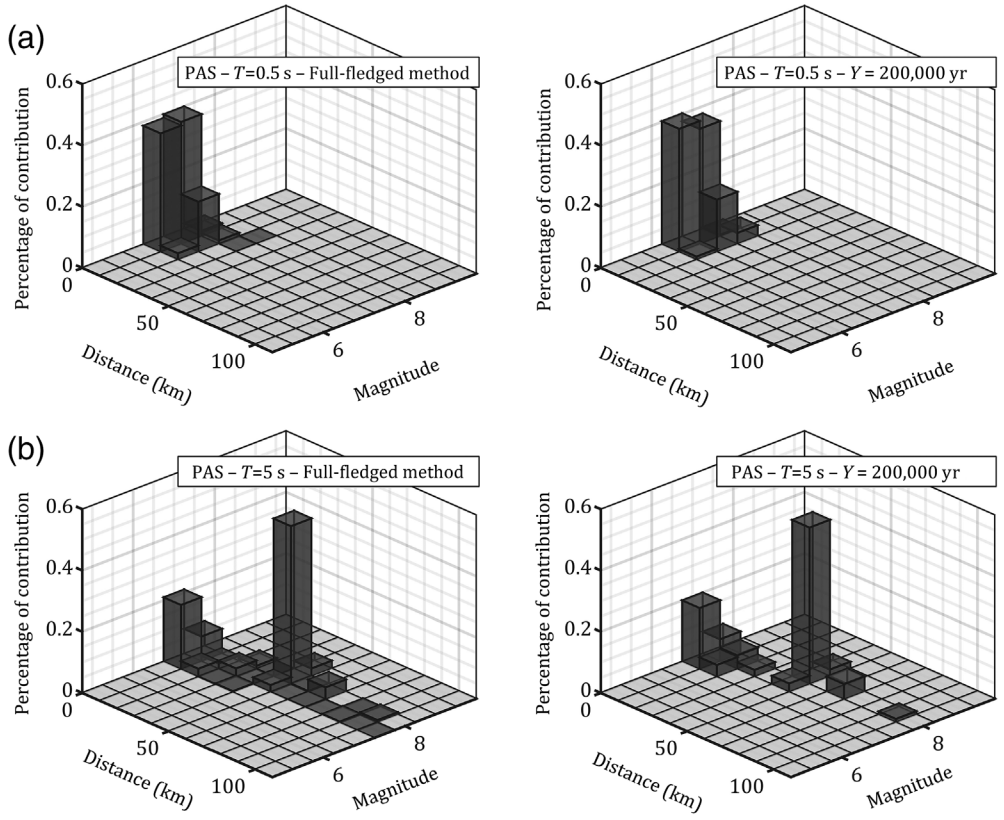

Figure 6. Magnitude–distance disaggregation at PAS for $S_a(T)$ at 5% PE in 50 yr from the (left) full-fledged method and (right) a 200,000 yr Monte-Carlo catalog for (a) $T = 0.5$ s and (b) $T = 5$ s.

disaggregation results at SUTB that are similar to the ranges observed at LADT, PAS, and SBSM, further verifying the applicability of the proposed approach.

CONCLUSIONS

The current CyberShake approach for performing PSHA at a site requires the simulation of ground motions for all the earthquake scenarios that affect the site, an average of 415,000 scenarios for sites in southern California. The SGTs are calculated around the site of interest and then postprocessed through seismic reciprocity to obtain the seismograms. As such, this so-called full-fledged method requires considerable computational resources due to the large number of earthquake scenarios and the important processing requirements imposed by the numerical simulations. This article presents a methodology that can reduce the computational requirements of the CyberShake platform by reducing the number of earthquake scenarios used in the analysis. The methodology is based on the Monte-Carlo simulation of earthquake catalogs of a specified duration at the site of interest. These catalogs specify a subset of earthquake scenarios to select among the complete set of scenarios that can affect the site.

Monte-Carlo earthquake catalogs with different lengths are developed at three locations in southern California with varying site, basin, and directivity conditions. The seismic hazard curves from the proposed Monte-Carlo approach are compared against the full-fledged method, and errors between the curves are quantified at the commonly used hazard levels. As expected, the accuracy of the hazard estimates from the Monte-Carlo approach increases with the duration of the catalog. A Monte-Carlo catalog with a duration of 200,000 yr is found suitable to represent the seismic hazard at a site for the range of periods and hazard levels of common engineering interest. For the sites considered in this study, such catalogs result in hazard curves with absolute relative errors having a median of 1.3% and a 95th percentile of 4.5% at a 2% PE in 50 yr hazard level. The number of ground motions required by a 200,000 yr earthquake catalog is 97% less than what is required by the current CyberShake approach. This reduction has a significant effect on the computational cost of the seismogram synthesis, which is reduced by more than 99%. If a lower level of accuracy is acceptable, the catalog duration can be further decreased, and a larger reduction in the number of earthquake scenarios and computational cost can be achieved. The results obtained at the three sites are generally comparable, which asserts the applicability of the Monte-Carlo approach independent of the site specificities. The similarity in the disaggregation patterns between the proposed and the full-fledged methods further highlights the potential of implementing the proposed approach in hazard calculations. The Monte-Carlo approach also proves to be valid for the seismic assessment of nonlinear degrading SDoF systems. Future studies should evaluate whether this approach can be extended to the probabilistic seismic demand analysis of more complex nonlinear structures using CyberShake simulations. In this case, the approach can act as a ground-motion selection tool that limits the number of dynamic analyses required at a site.

Physics-based ground-motion simulations are continuously improving and offer a reliable alternative to GMPEs in ground-motion characterization. Despite the usefulness of these numerical simulations in a broad range of engineering applications, the significant computational time and resources they require still impede their widespread use. Implementing Monte-Carlo catalogs in the current CyberShake framework

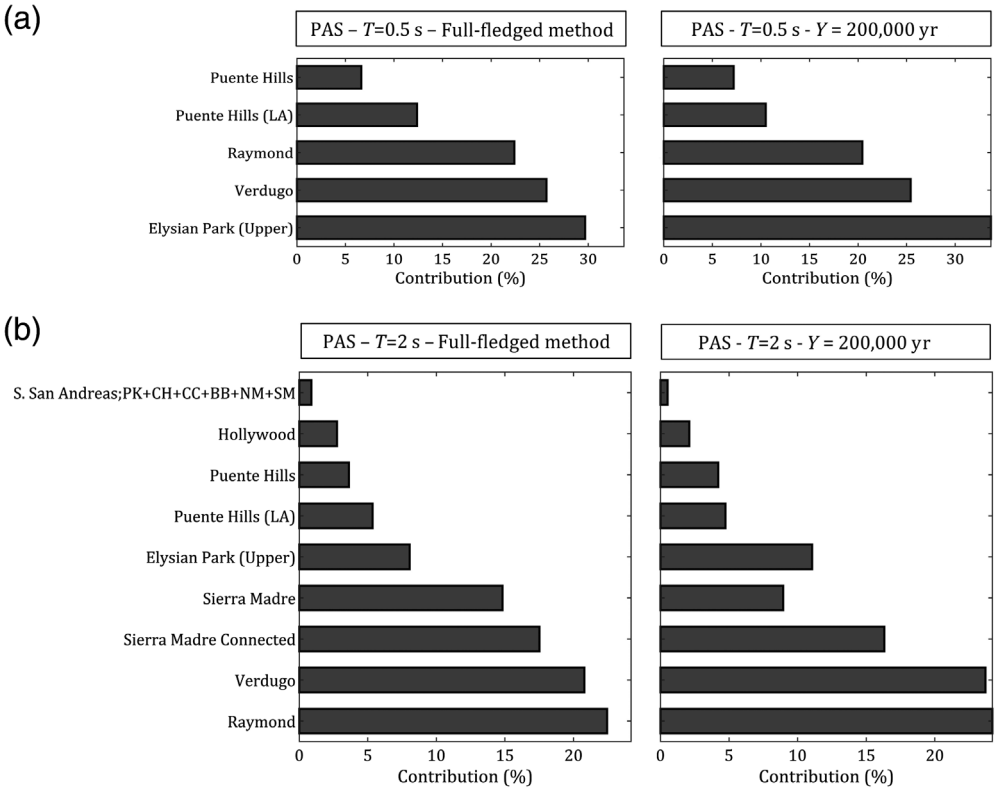

Figure 7. Source disaggregation at PAS for $S_a(T)$ at 5% PE in 50 yr from the (left) full-fledged method and (right) a 200,000 yr Monte-Carlo catalog for (a) $T = 0.5$ s and (b) $T = 2$ s.

addresses this drawback and offers a reliable and practical tool for performing simulation-based PSHA. By reducing the time-to-solution per site, hazard maps can be more easily updated (e.g., whenever any of the ground motion, ERF, source, or velocity models is updated or improved) or developed for new regions of interest (such as in CyberShake studies 17.3 and 18.8, which also use UCERF2 for central and northern California, respectively).

One of the advantages of implementing a Monte-Carlo simulation approach in PSHA is the flexibility that it provides, by its ability to accommodate any seismic source or earthquake occurrence model (Musson, 2000; Weatherill and Burton, 2010). These models can range from simple time-independent Poisson models, as used in this study, to more complex time-dependent occurrence models that consider spatiotemporal clustering. In the latter case, techniques such as the ones described in Zhuang and Touati (2015) can be used to generate a synthetic earthquake catalog based on the type of process governing earthquake occurrence. Future research can extend the application and validation of the approach of using Monte-Carlo earthquake catalogs and physics-based ground-motion simulations in PSHA to more recent empirical ERFs or more complex earthquake occurrence models. Another extension could consist of comparing the hazard estimates obtained using Monte-Carlo versus physics-based (e.g., RSQSim as in Milner *et al.*, 2021) earthquake catalog simulators. These studies can pave the way for a more rapid improvement in the field of ground-motion simulation.

DATA AND RESOURCES

The ground-motion time series used in this study were obtained from the Southern California Earthquake Center (SCEC). CyberShake data are also provided by the SCEC servers at the University of Southern California using MySQL. More information can be found on the following webpages: https://strike.scec.org/scecpedia/Accessing_CyberShake_Seismograms and https://strike.scec.org/scecpedia/Accessing_CyberShake_Database_Data. All websites were last accessed in October 2020.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge there are no conflicts of interest recorded.

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