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TALL BUILDING PERFORMANCE-BASED SEISMIC DESIGN USING SCEC BROADBAND PLATFORM SITE-SPECIFIC GROUND MOTION SIMULATIONS

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The scarcity of strong ground motion records presents a challenge for making reliable performance assessments of tall buildings whose seismic design is controlled by large-magnitude and close-distance earthquakes. This challenge can be addressed using broadband ground-motion simulation methods to generate records with site-specific characteristics of large-magnitude events. In this paper, simulated site-specific earthquake seismograms, developed through a related project that was organized through the Southern California Earthquake Center (SCEC) Ground Motion Simulation Validation (GMSV) Technical Activity Group, are used for nonlinear response history analyses of two archetype tall buildings for sites in San Francisco, Los Angeles, and San Bernardino. The SCEC GMSV team created the seismograms using the Broadband Platform (BBP) simulations for five site-specific earthquake scenarios. The two buildings are evaluated using nonlinear dynamic analyses under comparable record suites selected from the simulated BBP catalog and recorded motions from the NGA-West database. The collapse risks and structural response demands (maximum story drift ratio, peak floor acceleration, and maximum story shear) under the BBP and NGA suites are compared. In general, this study finds that use of the BBP simulations resolves concerns about estimation biases in structural response analysis which are caused by ground motion scaling, unrealistic spectral shapes, and over-conservative spectral variations. While there are remaining concerns that strong coherence in some kinematic fault rupture models may lead to an overestimation of velocity pulse effects in the BBP simulations, the simulations are shown to generally yield realistic pulse-like features of near-fault ground motion records.

KEYWORDS

SCEC Broadband Platform, site-specific ground motion simulation, tall building, code-based design, performance-based assessment

INTRODUCTION

Tall buildings represent an important portion of the business sector and an increasing portion of the residential sector of cities, damage to which can pose risks to the neighborhood and citywide recovery (e.g., ATC-119-1, 2018). This risk is compounded by the lack of strong ground motion records, especially in metropolitan areas of high seismicity, which presents a challenge for reliably assessing the performance of tall buildings under large-magnitude and near-source earthquakes. While there are over 21,000 records in the NGA-West2 database (Ancheta et al., 2014), only 84 of these are from earthquakes with magnitude of 7.5 or higher and within distances of 20 km. Consequently, when nonlinear dynamic analyses are used to substantiate the seismic design of tall buildings, they are run using scaled and/or spectrally matched available records, which can bias estimates of the earthquake response and safety (e.g., Dávalos and Miranda, 2019; Seifried and Baker, 2016). Compounding the scarcity of records are potential biases introduced by the ergodic assumptions inherent in conventional ground motion models (GMMs), where the distribution of ground motion characteristics at a given site is derived from ground motions recorded at universal locations that have the same earthquake magnitude, distance, and shear wave velocity among other parameters. This assumption overlooks the site-specific geologies that can influence earthquake ground motion characteristics. While

efforts are underway (e.g., Landwehr et al., 2016; Stewart et al., 2017; Kuehn et al., 2019) to develop nonergodic GMMs to better capture local geologic features, their development is limited by the scarcity of strong ground motion records.

Parallel to the development of empirical GMMs based on global databases, there have been significant advancements in the development and validation of numerical ground motion simulation models. By explicitly simulating the physical processes including fault rupture, wave propagation, and surficial site response, the simulated records have the advantage over global instrumented records of representing more realistic site-specific (nonergodic) ground motion characteristics. Ground motion simulation methods can generally be categorized into three classes: (1) stochastic methods (e.g., Rezaeian and Der Kiureghian, 2008), (2) deterministic fault-rupture-wave-propagation methods (e.g., Kozdon and Dunham, 2013), and (3) hybrid methods (e.g., Graves and Pitarka, 2014). The Southern California Earthquake Center (SCEC) Broadband Platform (BBP) is a collaborative software for hybrid simulation of ground motions with frequency from 0 to higher than 20 Hz including kinematic rupture generation, low- and high-frequency seismogram synthesis using 3D wave propagation through 1D layered velocity structures, nonlinear site effects, ground motion intensity measure calculations, and visualization (Maechling et al., 2015). Validation studies have been conducted for different applications: (1) seismic hazard analysis (e.g., Goulet et al., 2014; Dreger et al., 2014), (2) intensity measure prediction (e.g., Rezaeian et al., 2015), and (3) structural analysis (e.g., Burks and Baker, 2014; Bijelić et al., 2018; Galasso et al., 2013).

A project of the SCEC Ground Motion Simulation Validation (GMSV) Technical Activity Group (Luco et al., 2017) previously conducted BBP simulations for five site-specific earthquake scenarios to generate 2096 3D seismograms (Goulet et al., 2018) that provided an alternative to the recorded ground motions in the NGA-West database (Power et al., 2008). The scenarios were identified through seismic deaggregation of the dominant earthquake sources for three illustrative sites in San Francisco (SF), Los Angeles (LA), and San Bernardino (SB). This paper focuses on using the BBP site-specific ground motion records to assess the seismic performance of buildings under dominant earthquake scenarios. Two archetype tall buildings, a 20-story frame and a 42-story shear wall, were modeled and analyzed in OpenSees (McKenna et al., 2006) under comparable suites of ground motions selected from the simulated BBP and recorded NGA databases. Based on the nonlinear response history analysis results, the structural response demands (maximum story drift ratio, peak floor acceleration, and maximum story shear) and collapse risks are compared for the two sets of ground motions. Statistical inferences between the two are made, and the observed agreement and differences between the two are discussed to advance the application of BBP simulated records.

ARCHETYPE TALL BUILDINGS

The two tall buildings used in this study are (1) a 20-story reinforced concrete special moment frame and (2) a 42-story reinforced concrete shear wall. The 20-story frame (originally studied in the FEMA P-695 project, ID 1020) was designed per ASCE 7-05 for the Seismic Design Category D maximum (i.e., $S_{M1} = 0.9g$), and the design was mainly controlled by the minimum seismic base shear (strength) and drift (minimum stiffness) requirements (FEMA, 2009). This study idealized the frame as a 2D analytical model in OpenSees where the first three modal periods are 2.6s, 0.9s, and 0.5s (Figure 1a). The moment frame system was modeled with concentrated plastic hinges in beams and columns, a nonlinear beam-column joint panel zone, and a leaning column to capture the P- Δ effects from the gravity system. The lumped plastic hinge employed the phenomenological Ibarra-Medina-Krawinkler model (Ibarra et al., 2005), where the cyclic degradation parameters have been calibrated to capture the in-cycle and cyclic deterioration observed in the laboratory (Haselton and Deierlein, 2007).

The 42-story shear wall building (Figure 1b), originally developed in the PEER Tall Building Initiative (TBI) project (Moehle et al., 2011), was designed per the performance-based method by fulfilling the performance targets under MCE (2475-year return period) and SLE (43-year return period) with $S_a(1s) = 0.9g$ and $0.2g$, respectively. It has a continuous reinforced concrete core consisting of two major C-shape shear walls. In this study, the building was idealized as a 2D model whose first three modal periods are 4.2s, 1.0s, and 0.5s. The weak-direction core wall system was simplified as a C-shape shear wall, connected with a leaning column to capture the P- Δ effects from the gravity system. The shear-wall was modeled by force-based beam-column elements, where each story was modeled by one element with 6 Gauss-Lobatto integration points. Each integration point contains one detailed fiber section with the regularized concrete (Concrete02) and steel (Steel02) materials to model flexure responses (Pugh et al., 2015), and one shear section to approximate elastic shear responses. Rayleigh damping was applied in both the frame and wall models, with critical damping ratios of 5.0% (frame) and 2.5% (wall).

Figure 1. Archetype tall buildings and analytical models. (a) FEMA P695 – 20-story RC frame modeled with lumped plastic hinge model. (b) PEER TBI – 42-story wall modeled with fiber-based beam-column model (the standard-story plan view is adapted from Moehle et al., 2011).

SITES AND SEISMIC HAZARD

The SCEC GMSV project (Luco et al., 2017) identified three illustrative building sites for this project in downtown San Francisco, downtown Los Angeles, and San Bernardino. Basic information for the sites is summarized in Table 1, including their locations, site classes, and ASCE 7-16 Risk-Targeted Maximum Considered Earthquake (MCE_R) intensities (ASCE, 2016; BSSC, 2015). The San Francisco site class B location is the least intense with S_{M1} equal to 0.48g. The Los Angeles site class C location has S_{M1} equal to 0.98g, and the San Bernardino site class D location has the largest intensity of S_{M1} equal to 1.48g.

Table 1. Basic information and seismic intensities of three sites.

Site	Latitude	Longitude	Site class	V_{s30} (m/s)	S_S (g)	S_1 (g)	S_{MS} (g)	S_{M1} (g)
San Francisco	37.786 N	122.391 W	B	873	1.50	0.60	1.35	0.48
Los Angeles	34.052 N	118.257 W	C	390	1.97	0.70	2.37	0.98
San Bernardino	34.104 N	117.288 W	D	280	2.19	0.87	2.19	1.48

The fundamental periods of the two archetype buildings are 2.6s and 4.2s, respectively. In this study, the seismic hazard was conditioned on periods of 3s and 5s so that the seismic deaggregation can be directly obtained from standard U.S. Geological Survey (USGS) tools (USGS, 2020). Based on the seismic deaggregation, the major seismic sources at two conditioning periods across intensity levels for the three sites are summarized (e.g., $T = 3.0$ s results corresponding to 2% probability of exceedance in 50 years are illustrated in Figure 2). At the San Francisco site, the dominant seismic source is the Northern San Andreas fault, while the Hayward-Rodgers Creek fault contributes less than 10% of the total hazard. At the Los Angeles site, the hazard attribution is more diverse, where (1) the nearby Elysian Park fault contributes 15% to 30% of the total hazard (dependent on the period and the intensity level), (2) the Southern San Andreas fault contributes 10% to 30% of the hazard, and the remaining contribution is attributed to other near-by fault systems. At the San Bernardino site, the San Jacinto fault contributes 55% to 80% of the hazard, and the rest is attributed to the Southern San Andreas fault. Based on the seismic sources and corresponding earthquake magnitudes that dominate the hazard at the three building sites, the following five earthquake scenarios were simulated in the SCEC GMSV project (Luco et al., 2017): (1) Mw 8.0 Northern San Andreas, (2) Mw 7.0 Hayward-Rodgers Creek, (3) Mw 6.6 Elysian Park, (4) Mw 7.9 Southern San Andreas, and (5) Mw 7.8 San Jacinto.

Figure 2. Dominant seismic hazard sources at the three sites for period of 3s corresponding to 2% probability of exceedance in 50 years. (a) San Francisco. (b) Los Angeles. (c) San Bernardino (after Luco et al., 2017; USGS 2020).

BBP SITE-SPECIFIC SIMULATIONS

The BBP simulations used in this study are based on the GP method (Graves and Pitarka, 2010, 2014, and 2016). At frequencies below 1 Hz, the method adopts a theoretically rigorous and deterministic representation of fault rupture and wave propagation effects. At frequencies above 1 Hz, it uses a stochastic representation of source radiation. The two components are combined in the frequency domain and converted to a single time history. A deterministic 1D soil velocity model was used with multiple surrogate stations for each site with similar distances and soil classes to represent variability in path effects on wave propagation (Goulet et al., 2018). Frequency-dependent nonlinear site amplification factors, based on V_{S30} (Boore et al., 2014), are used to represent the surficial site effects.

As noted previously and summarized in Table 2, five earthquake scenarios were simulated on the five fault systems. For each scenario and its magnitude, multiple fault rupture realizations were considered with varying hypocenters and rupture progressions. The kinematic rupture generator used variable spatial and temporal kinematic rupture parameters that were calibrated using recorded ground motions and observed rupture kinematics. Details of the 4192 horizontal seismograms generated for the five earthquake scenarios are summarized in Table 2 (Goulet et al., 2018). Note that the V_{S30} values for some of the stations used in the BBP simulations (Table 2) differ from those at the building sites (Table 1). These discrepancies were the result of trade-offs in characterizing the geologic velocity structures for the BBP simulations and are not expected to have a significant effect on the outcomes of the study.

A fault rupture simulation for one of the Northern San Andreas earthquake realizations is illustrated in Figure 3a, which shows the slip distribution (color shading) and rupture fronts by time (black contours). This is one of 16 realizations of the Northern San Andreas M8.0 with a hypocenter located close to San Francisco that ruptured a region about 470 km long and 12 km deep. As listed in Table 2, 6 different hypocenters (-200 km, -100 km, 0 km, 90 km, 150 km, and 210 km) along the fault strike were used to simulate ground motions at 6 stations (triangles in Figure 3a), which are located at distances from the fault rupture that are representative of the building site. For the case shown in Figure 3a, the hypocenter was located at 90 km (relative to the midpoint of the rupture) and -8 km deep and propagated bi-directionally for about 2 minutes over the rupture length. The black contours in Figure 3a represent 2-second intervals of the rupture front, where the peak slips range up to about 2500 cm. Figures 3b and 3c show the resulting N-S and E-W seismograms at two of the six stations where ground motions were simulated. The difference in arrival times and amplitudes of these two ground motions reflect the distance of the sites from the earthquake hypocenter.

Figure 3. BBP Simulation (after Goulet et al., 2018). (a) Fault rupture realization of Northern San Andreas Earthquake. (b) Simulated N-S ground acceleration. (c) Simulated E-W ground acceleration.

Table 2. Earthquake scenarios and horizontal seismograms in the BBP database (Goulet et al., 2018).

Scenario	M	R (km)	V_{S30} (m/s)	Seismograms	Hypocenters	Stations	Realizations
Northern San Andreas	8.0	13.4~45.1	863~873	1152	6	6	16
Hayward/Rodgers Creek	7.0	14.2~22.2	863~873	576	3	6	16
Elysian Park	6.6	3.2~5.9	280~446	704	2	11	16
Southern San Andreas	7.9	3.2~5.9	280~446	352	8	22	1
San Jacinto	7.8	0.4~4.2	280~495	1408	4	11	16

The response spectra of unscaled BBP seismograms from the Northern San Andreas and Hayward/Rodgers Creek earthquakes are compared in Figure 4a with target conditional mean spectra (CMS) for the San Francisco building site (Baker, 2010). The CMS were computed using the ground motion model (Campbell and Bozorgnia, 2008) and intensity measure correlation model (Baker and Jayaram, 2008) with the deaggregated mean magnitude and distance values (Table 3), soil velocity (Table 1), and corresponding conditioning period. Because these seismograms were generated by the dominant magnitude events and local soil conditions, they naturally represent the 2% probability of exceedance in 50- and 200-year (2/50 and 2/200) CMS targets. In contrast, as shown in Figure 4b, there are not enough high intensity recorded records in the NGA-West catalog to reliably characterize the CMS targets for the 2/50 and 2/200 exceedance probabilities, especially for the longer conditioning period ($T = 5$ s). This limitation is even more apparent for the other two sites, where their MCE_R intensities are about 2 to 3 times higher than the San Francisco site (Table 1). This promising feature of the BBP simulations, i.e., naturally capturing the high-intensity spectral shape characteristics, will be further illustrated by the case studies in the following sections.

Figure 4. Comparison of unscaled response spectra of ground motions and conditional mean spectra (CMS). (a) BBP (Northern San Andreas M8.0 and Hayward M7.0). (b) NGA-West.

APPLICATION TO CODE-BASED DESIGN

Following the requirements for nonlinear response history analyses in ASCE 7-16 (ASCE, 2016), suites of 11 ground motion records were selected and scaled from the NGA and BBP databases such that their average response spectrum is not less than 90% of the target response spectrum within the specified period range of $0.2T_1$ to $1.5T_1$, where T_1 is the first modal period ($T_1 = 3.0$ s and 5.0 s for the two archetypes in this study). Figure 5 shows the response spectra of the selected records and the target MCE_R code-specified spectrum of the San Francisco site. Note that following the default ASCE 7-16 guidelines, the MCE_R spectrum drops off at $1/T$. Similar selections were made for the Los Angeles and San Bernardino sites (more details for all three sites are available in the digital appendix: <https://purl.stanford.edu/vd748js9648>).

Figure 5. Response spectra of selected ground motions (San Francisco, MCE_R target). (a) NGA ($T_1 = 3$ s). (b) BBP ($T_1 = 3$ s). (c) NGA ($T_1 = 5$ s). (d) BBP ($T_1 = 5$ s).

Nonlinear response history analyses were then conducted for the two buildings under the selected NGA and BBP ground motion suites. The resulting maximum story drift ratio (SDR_{max}), peak floor acceleration (PFA), and story shear profiles along the building height are shown in Figure 6 for the San Francisco site. These comparisons indicate that where the average response spectra of the BBP and NGA records are closely fit to the same target spectrum (Figure 5), the resulting average responses are similar.

Figure 6. Average structural responses of two tall buildings under BBP and NGA record suites (San Francisco, MCE_R target). (a) 20-story frame. (b) 42-story wall.

Since the BBP records were simulated for each specific site, there was no need to apply criteria other than selecting and scaling records to match (on average) the target MCE_R spectrum. On the other hand, the selected NGA records were constrained to have the same general tectonic setting and similar magnitudes as the target hazard. The algorithm for record selection and scaling, which is available in the digital appendix, is based on a modified version of one by Jayaram et al. (2011). In addition, the scaling factor applied to NGA records was limited to 6, which is comparable to the maximum scaling allowed for the BBP records. Figure 7a shows the magnitudes and distances of the selected NGA records, as compared to the target values shown by the dashed lines, and Figure 7b compares the scaling factors of the selected NGA and BBP records. As illustrated in Figure 7b, the statistical selection to match the MCE_R target results in about half of the 11 BBP records coming from the Hayward scenario, which is inconsistent with the fact that the hazard for San Francisco is dominated by the San Andreas fault. In addition, the selected BBP Hayward records typically have larger scaling factors than those of the selected BBP Northern San Andreas records. As illustrated in Figure 7c, this inconsistency arises mainly because the spectral shapes of Hayward records are closer to the “1/T” shape of the MCE_R spectrum, which does not necessarily represent the spectral shape of large (i.e., M8) earthquakes that control the hazard in San Francisco. Referring to Figure 4a, because of the smaller magnitude, the Hayward response spectra typically drop off as a function of period faster than those of Northern San Andreas records.

Figure 7. Features of selected ground motions (San Francisco). (a) Causal parameters (M_w and R) of selected NGA records. (b) Scaling factors. (c) Spectra of selected BBP records and MCE_R target.

As an alternative to the MCE_R spectrum, ASCE 7-16 allows use of a CMS-based target spectrum, which is considered to represent a more realistic spectral shape given a specific scenario, accounting for correlation in spectral accelerations about a specified conditioning period. To assess the influence of spectral shape, the BBP and NGA ground motions were re-selected to match the 2/50 CMS of the San Francisco site. The response spectra of the re-selected records are shown in Figure 8a and Figure 8b, along with the associated scaling factors in Figure 8c. In contrast to the previous selection for the MCE_R target, in this case the selection algorithm chose only BBP records associated with the M8.0 Northern San Andreas event, which is a naturally better match to the 2/50 CMS target. Moreover, the average scaling factors for these BBP records were only 1.1 and 1.2 for the $T_1 = 3s$ and $5s$ CMS, respectively. On the other hand, the selected NGA records had average scaling factors of 4.1 and 5.6 for $T_1 = 3s$ and

5s, respectively (Figure 8c). As indicated in the previous study by Chandramohan et al. (2016a), neglecting the ground motion duration effect can cause potential biases in estimated structural performance. In this regard, the BBP simulations of the M8.0 Northern San Andreas Earthquake help to overcome the current shortage in long duration records from large magnitude earthquakes. As shown in Figure 8d, the cumulative distributions of 5%-75% significant duration (DS_{5-75}) of the selected BBP records are closer to the median 2/50 hazard targets than the NGA records, where the DS_{5-75} targets were computed based on the 2/50 seismic deaggregation information and the ground motion prediction equation by Afshari and Stewart (2016).

Figure 8. Ground motion selection results (San Francisco, CMS target). (a) Response spectra ($T_1 = 3s$). (b) Response spectra ($T_1 = 5s$). (c) Scaling factors. (d) Significant duration (DS_{5-75}).

The resulting SDR_{max} , PFA , and story shears under the BBP and NGA CMS-targeted records are compared in Figure 9. In general, the average responses for the NGA records are greater than those for the BBP records. The differences in the PFA demands are caused by the discrepancy between the NGA spectra and the CMS target at short periods (Figure 8a and Figure 8b). Similarly, the SDR_{max} values for the upper stories of the 42-story building are higher for the NGA motions, presumably due to the short period (higher mode) response. These results further substantiate the comparison of ground motion characteristics, which indicate that the BBP motions for the M8.0 the Northern San Andreas scenario are more representative of the CMS (2/50) target. Similar comparisons are observed between the BBP and NGA record suites at the Los Angeles site (more details: <https://purl.stanford.edu/vd748js9648>).

Figure 9. Average structural responses of two buildings under BBP and NGA record suites (San Francisco, CMS target). (a) 20-story frame. (b) 42-story wall.

At the San Bernardino site, the discussion here is mainly focused on the 42-story wall building, since the 20-story moment frame is underdesigned for that site and most of the MCE_R records cause collapse of the model, i.e., 7 collapses out of the 11 NGA records and 10 collapses out of the 11 BBP records. As shown in Figure 10, although the average response spectra of the BBP and NGA ground motion suites fit well to the target MCE_R spectrum, the spectral values of the BBP records are much smaller than those of the NGA records at periods below 1.0s. This difference leads to the average PFA demands under BBP records being 30%~40% smaller than those under the NGA records (Figures 10c and 10d). Of the 11 records in each set, 6 BBP records and 4 NGA records are identified to be pulse-like, based on the pulse index by Baker (2007). In general, the average SDR_{max} demands under the BBP records are roughly 30% larger than those under the NGA records. Given the limited number of 11 records in each set, the pulse-like records (highlighted in dark gray in Figures 10c and 10d) tend to control the average SDR_{max} demands. On the other hand, the average base shear under the BBP records is about 30% smaller than that under the NGA records, which is probably due to the difference in the short-period spectra (Figure 10a and 10b). Based on these observations, at the sites subject to strong near-fault features, it is important to be mindful of the number and intensity of pulse-like records out of the 11 selected records and differences in spectra at short periods. Other related features (e.g., pulse periods and spectral shapes) will be discussed later in the section on performance-based assessment.

Figure 10. Response spectra of selected ground motions and wall responses (San Bernardino, MCE_R target).
(a) Response spectra of NGA records. (b) Response spectra of BBP records. (c) Wall responses under NGA records. (d) Wall responses under BBP records.

APPLICATION TO PERFORMANCE-BASED ASSESSMENT

Going beyond the building code procedure of checking conformance with MCE_R minimum acceptance criteria, we compared the BBP and NGA records using a more complete performance-based assessment, as follows. First, seismic deaggregation information was obtained for the given site at three probability levels (10% in 50 years, 2% in 50 years, and 2% in 200 years). For instance, Table 3 shows the seismic deaggregation information for the San Francisco site, where the hazard is dominated by earthquakes on the San Andreas fault. Where the site hazard is attributed to several sources, as it is for the Los Angeles and San Bernardino sites, the source-specific deaggregation was obtained (Tables 4 and 5). Second, based on the seismic deaggregation results, the intensity measure targets were evaluated. The comprehensive target in this study adopts the generalized conditional intensity measure (GCIM) approach (Bradley, 2010), which combines the conditional spectrum (CS) (Lin et al., 2013) and the conditional significant duration (Chandramohan et al., 2016b) approaches. For the San Francisco site, a single site-specific GCIM target was used at

each intensity level considering the dominant source contributes to more than 90% of the seismic hazard. For the other two sites, multiple source-specific GCIM targets were developed for individual scenarios. Third, based on the adapted ground motion selection algorithm (Jayram et al., 2011), 100 records were selected to best fit the GCIM target(s) at each intensity level. These records were scaled so that (1) the median and dispersion of spectral values at periods from 0.1 s to 10 s match the target conditional spectrum; and (2) their DS_{5-75} distribution matches the target conditional DS_{5-75} distribution. Note that for the Los Angeles and San Bernardino sites, ground motion subsets were selected for individual sources with numbers defined by the seismic hazard deaggregation weights (Lin et al., 2013, Chandramohan et al., 2016b). This source-specific procedure offers the benefits of (1) rigorously representing peculiar spectral and duration characteristics of different sources and (2) comparing structural responses under BBP and NGA records in a specific scenario (e.g., Elysian Park only). Finally, nonlinear response history analyses were conducted, and the resulting demand distributions of SDR_{max} and PFA , and collapse risks, were contrasted for the BBP and NGA record sets.

Table 3. Seismic deaggregation information for the San Francisco site.

Period (T_1)	$T_1 = 3s$				$T_1 = 5s$			
Exceedance Prob.	Sa (g)	R (km)	M	ϵ	Sa (g)	R (km)	M	ϵ
10% in 50 years	0.102	19.6	7.64	0.74	0.059	15.5	7.63	0.71
2% in 50 years	0.199	15.4	7.80	1.38	0.122	14.4	7.79	1.38
2% in 200 years	0.303	14.1	7.87	1.83	0.191	14.2	7.86	1.84

Note: Deaggregations were obtained from <https://earthquake.usgs.gov/nshmp-haz-ws/>.

Table 4. Seismic deaggregation information for the Los Angeles site.

Period (T_1)	$T_1 = 3s$						$T_1 = 5s$					
Exceedance Prob.	Sa (g)	Source	Contr. (%)	R (km)	M	ϵ	Sa (g)	Source	Contr. (%)	R (km)	M	ϵ
10% in 50 years	0.146	EP	18	4.0	6.58	0.57	0.082	EP	13	4.0	6.59	0.70
		SSA	21	55.6	7.82	1.39		SSA	26	55.6	7.77	1.37
		Others	61	23.8	7.04	0.98		Others	61	28.3	7.11	1.03
2% in 50 years	0.265	EP	25	4.0	6.59	1.44	0.150	EP	18	4.0	6.60	1.49
		SSA	13	55.6	7.99	2.14		SSA	21	55.6	7.87	2.00
		Others	62	14.8	7.05	1.40		Others	61	18.1	7.15	1.45
2% in 200 years	0.393	EP	29	4.0	6.60	2.00	0.225	EP	22	4.0	6.62	2.01
		SSA	7	55.6	7.99	2.54		SSA	14	55.6	8.00	2.32
		Others	64	11.8	7.12	1.69		Others	65	14.8	7.19	1.76

Note: EP: Elysian Park. SSA: Southern San Andreas. Deaggregations were obtained from <https://earthquake.usgs.gov/nshmp-haz-ws/>.

Table 5. Seismic deaggregation information for the San Bernardino site.

Period (T_1)	$T_1 = 3s$						$T_1 = 5s$					
Exceedance Prob.	Sa (g)	Source	Contr. (%)	R (km)	M	ϵ	Sa (g)	Source	Contr. (%)	R (km)	M	ϵ
10% in 50 years	0.411	SSA	41	9.1	7.82	0.79	0.239	SSA	44	9.2	7.81	0.75
		SJ	59	1.4	7.00	0.74		SJ	56	1.4	7.76	0.65
2% in 50 years	0.809	SSA	29	8.9	7.92	1.61	0.496	SSA	33	8.9	7.90	1.53
		SJ	71	1.4	7.77	0.97		SJ	67	1.4	7.77	0.94
2% in 200 years	1.234	SSA	19	8.9	7.97	2.04	0.780	SSA	23	8.9	7.97	1.97
		SJ	81	1.4	7.78	1.51		SJ	77	1.4	7.78	1.48

Note: SSA: Southern San Andreas. SJ: San Jacinto. Deaggregations were obtained from <https://earthquake.usgs.gov/nshmp-haz-ws/>.

Site 1: San Francisco

The GCIM (i.e., CS and significant duration) targets were evaluated using the ground motion models (Campbell and Bozorgnia, 2008; Afshari and Stewart, 2016) and intensity measure correlation models (Baker and Jayaram, 2008; Bradley, 2011). For instance, for the intensity level with 10% in 50-year exceedance (10/50), the target conditional spectrum (conditioning period of 3s) and the target conditional DS_{5-75} distribution for the San Francisco site are shown by the green curves in Figure 11a. In Figure 11b, the response spectra and the DS_{5-75} distributions from the selected BBP and NGA record suites are compared, and the resulting fitting qualities are similar for the two record suites at all three intensity levels.

Figure 11. Response spectra and significant duration of selected records at the San Francisco site (GCIM target: CS and significant duration). (a) BBP records at $T_1 = 3$ s (10%/ in 50 years). (b) Comparison of response spectra and duration distributions of NGA and BBP ground motion suites ($T_1 = 3$ s).

To investigate the statistical significance of the differences between the estimated story responses under the NGA and BBP records, a two-sample two-sided t-test (e.g., DeGroot and Schervish, 2012) was used. The t-test examines the hypothesis that the estimated responses under the BBP and NGA record sets are equal in terms of their logarithmic mean and variance. The hypothesis test results are shown in Figure 12, where all tested story responses lie within the $\pm 5\%$ bounds, indicating there is no statistically significant difference between the estimated demands from the two ground motion suites.

Figure 12. Hypothesis tests for estimated SDR_{max} and PFA demand distribution at the San Francisco site (GCIM target: CS and significant duration). (a) The 20-story frame. (b) The 42-story wall.

To investigate the differences in collapse risk, the number of collapses was counted at each intensity level (Figure 13a). Collapse fragilities are then developed using the maximum likelihood method (Baker, 2015) for both record suites (Figure 13b). Integrating the collapse fragilities with respect to the mean annual exceedance rate of S_a (obtained from <https://earthquake.usgs.gov/nshmp-haz-ws/>), the mean annual collapse rates under the BBP and NGA records are $6.4e^{-4}$ and $5.6e^{-4}$, respectively (Figure 13c). Summarizing the observations above, where the selected NGA and BBP records are matched to the same GCIM target with similar fitting qualities, there is no statistically significant difference in the estimated structural response demands and collapse risks.

Figure 13. Collapse assessments under NGA and BBP motions (San Francisco) (GCIM target: CS and significant duration). (a) Maximum SDR under three intensities. (b) Collapse fragilities. (c) Mean annual exceedance rates of maximum SDR .

Site 2: Los Angeles

Similar to the observations for the San Francisco site, no statistically significant difference was found in the estimated SDR_{max} and PFA demands under the NGA and BBP records that were selected for the CS and significant duration targets for the Los Angeles site. However, at the highest ground motion intensity level (2/200 probability of exceedance), a prominent difference is observed in the number of collapse instances under the BBP and NGA records for the Elysian Park source. Since the Los Angeles downtown site has multiple earthquake sources contributing significantly to the hazard, source-specific CS was used for each (Lin et al., 2013). As shown in the top row of plots in Figure 14, four ground motion suites of 29 records each (consistent with the proportional contribution of Elysian Park to the total hazard) were selected for comparative purposes: (a) NGA with records selected without limits on scaling or causal earthquake features, (b) NGA-C with filters to limit record selection to earthquakes of M6 to M7 and fault rupture distances of 0 to 10 km; (c) NGA-C&S with records selected with the causal limits in (b) and scaling factors of 5 or less; and (d) BBP with records simulated from the BBP Elysian Park M6.6 scenario. Although the median spectra of these four record suites are similar, the spectral variations are rather different. The BBP spectra have the least deviation from their median spectrum, whereas the NGA and NGA-C spectra have much larger deviations. This is related to the trend that adding constraints increases the number of motions selected from local earthquake events, where the NGA, NGA-C, and NGA-C&S sets include 2, 11, and 17 records (out of 29 total) from the 1994 Northridge Earthquake, respectively. Since the NGA-C&S and BBP records are intrinsically more representative of ground motions expected from the Elysian Park fault, as compared to records selected to match the ergodic conditional spectra targets, one can argue that their lower variability is in fact more representative of the hazard from the Elysian Park fault ruptures.

In the bottom row of plots in Figure 14, the spectra of Elysian Park records causing structural collapse in the analyses are highlighted in red, where the number of collapses are 5, 6, 2, and 0 for the NGA, NGA-C, NGA-C&S, and BBP records, respectively. As expected, the records that cause collapse typically have higher S_a 's at periods longer than T_1 , which demonstrates how the number of collapse instances is related to the variations in the spectra. To the extent that the simulated BBP records are more representative of the actual hazard, which is consistent with their similarity to the NGA-C&S records from the 1994 Northridge Earthquake, these results demonstrate the benefit of using earthquake simulations to better represent the seismic hazard compared to conditional spectra that are based on ergodic ground motion prediction equations.

Figure 14. Response spectra of selected ground motions ($T_1 = 3$ s) for the Elysian Park scenario (2/200) (CS target with site-specific reselection). (a) NGA. (b) NGA-C. (c) NGA-C&S. (d) BBP (Elysian Park records).

Note that results described in Figure 14 data are limited to the ground motion hazard from the Elysian Park scenario, which does not include collapse risk from the Southern San Andreas scenario and the other contributing faults to the seismic risk for the Los Angeles site. As shown in Figure 15, when the combined contributions are considered, the differences in total collapse risks between the methods are not as large. This reflects the fact that the large contribution from the other non-simulated faults does not differ between the recorded and simulated earthquake records. Nevertheless, this comparison for the Los Angeles site highlights the potential for site-specific simulated ground motions to more realistically represent the earthquake risk. Similar trends to those of the 20-story frame are found in the results of the 42-story wall (Figure 16), where the SDR_{max} demands for the BBP and NGA-C&S record sets are slightly less than those of the generalized NGA and NGA-C record sets.

Figure 15. Collapse risks of the 20-story frame estimated under the four ground motion suites (Los Angeles) (CS target with site-specific reselection). (a) Maximum SDR at three intensity levels. (b) Collapse fragilities. (c) Mean annual exceedance rates of maximum SDR .

In a strict sense, these comparisons are beyond the realm of verification or validation, since neither the selected NGA nor BBP record sets are known to be the “ground truth”. Moreover, the adopted ergodic ground motion prediction equations may lead to biases in the median spectra and an overestimation in the spectral variation. For a specific earthquake source, one would expect the aleatory uncertainty of spectral values to be smaller than the mixed-source (ergodic) condition. This is supported by the observation that the spectral variation is less in the NGA record suites consisting of more records from the 1994 Northridge earthquake, which had a similar magnitude (M6.7) and mechanism (blind thrust) as the Elysian Park scenario. As discussed previously, the reduced spectral variation leads to lower collapse rates and median SDR_{max} demands for the NGA-C&S and BBP record sets. This tendency suggests that using the BBP simulation has the advantage of avoiding the potential estimation bias in structural response analysis caused by the larger spectral variation when using ergodic ground motion models for a given site-specific seismic source.

Figure 16. Median response spectra of selected ground motions and estimated median SDR_{max} of the 42-story wall (Los Angeles) (CS target with site-specific reselection). (a) Median spectra (2% in 200 years). (b) Median SDR_{max} (2% in 200 years).

Site 3: San Bernardino

At the San Bernardino site, the dominant hazard is from the San Jacinto fault system (Table 5). For the reasons mentioned previously in the MCE_R design check, only the results of the 42-story wall are discussed here. Shown in Figure 17a are response spectra of the 1408 BBP records for the San Jacinto scenario, where the median spectrum is highlighted in red. Also shown, in blue, is the median and upper/lower bound spectra obtained using the Campbell and Bozorgnia (2008) ground motion prediction model for an earthquake of M7.8 and distance of 1.4 km. The “valley” observed in the median BBP spectrum at around $T = 0.8$ s is thought to be the result of a limitation of the synthesis method adapted in the GP BBP simulation method, since the low-period content (around $T = 1$ s) of the simulated ground motions is relatively strong in the near-fault region, as compared to the other sites. As a result, the empirically calculated stochastic portion of the record may not match well the conditions encountered for this earthquake scenario.

Among the 1408 San Jacinto records, 487 records were classified to be pulse-like following Baker’s pulse index method (Baker, 2007). Figure 17b shows the cumulative distribution of the pulse periods of these records, where the median value is 10s. As was done for the other two sites, ground motions were selected and scaled to match the conditional spectra target, and the resulting median response spectra of the selected BBP and NGA records are compared in Figure 17c. The median spectra for both the BBP and NGA record sets are close to the target CMS spectra at the 10/50 and 2/50 intensity levels, but much lower scaling was required for the BBP records. The amount of required scaling can be inferred from Figure 17d, where the median spectra of the unscaled BBP and NGA record sets (i.e., the sets selected for the San Jacinto scenario) are compared to the target 2/50 CMS. The median spectra are shown separately for the pulse and non-pulse records to show how pulse effects are an important contributor to the hazard for this near-fault site.

The selected BBP and NGA records were also classified by the pulse index method, where the number of selected records with pulse characteristics are summarized in Figure 17e. The pulse periods of the selected records are compared in Figure 17f, where the median pulse periods of the NGA records are consistently shorter than the median pulse periods of the BBP records. Using an empirical equation for pulse period (Baker, 2007), the median “target” pulse period for a M7.8 earthquake is 8.5s, which is better represented by the BBP record sets as compared to the NGA record sets. From an engineering perspective, pulses with periods on the order of 2 to 3 times the first-mode building period have been shown to be detrimental to structural performance, implying that the pulses with periods of 10s to 15s could be damaging to tall buildings with periods of 3s to 7 s (e.g., Alavi and Krawinkler, 2004, Champion and Liel, 2012).

Figure 17. Ground motion characteristics of the San Jacinto scenario. (a) Response spectra of BBP records. (b) Pulse periods of BBP records. (c) Response spectra of selected and scaled records. (d) Unscaled response spectra of selected records. (e) Pulse-like classification. (f) Pulse periods of selected records.

The S_a intensity and spectral shape effects can be captured by the average spectral acceleration, $S_{avg}(T_a-T_b)$, defined as the geometric mean of spectral accelerations over the period range T_a to T_b (Baker and Cornell, 2006; Eads et al, 2015). Two average spectral acceleration measures, $S_{avg}(1s-10s)$ and $S_{avg}(0.5s-1s)$, are used to differentiate the spectral intensities in the long and short period portions of the spectra. As shown in Figure 18a, the median values of $S_{avg}(1s-10s)$ of the BBP and NGA records are similar, and as would be expected, the corresponding median SDR_{max} demands are also similar (Figure 18c). The differences between SDR_{max} under the pulse records are roughly proportional to the differences between the corresponding $S_{avg}(1s-10s)$. By contrast, the difference in the median $S_{avg}(0.5s-1s)$ values for the BBP and NGA records is more prominent (Figure 18b). The selected BBP records typically have smaller median $S_{avg}(0.5s-1s)$ values than the median $S_{avg}(0.5s-1s)$ of the corresponding NGA records. Specifically, compared with the median $S_{avg}(0.5s-1s)$ values of the NGA pulse records, the median $S_{avg}(0.5s-1s)$ values of the BBP pulse records are 17% and 25% smaller under 10/50 and 2/50, respectively. This yields median PFA values under BBP pulse records that are 15% to 30% smaller than the median PFA values under NGA pulse records (Figure 18d). The smaller $S_{avg}(0.5s-1s)$ values of the BBP records are related to the “valley” in the BBP spectra, noted previously. Given the positive correlation observed between the median $S_{avg}(0.5s-1s)$ and median PFA , future studies are suggested to examine the $S_{avg}(0.5s-1s)$ of near-fault BBP records and to validate their accuracy of predicting floor acceleration demands.

Figure 18. Median Sa_{avg} values of selected NGA and BBP records for the San Jacinto scenario and resulting 42-story building responses. (a) Median $Sa_{avg}(1s-10s)$. (b) Median $Sa_{avg}(0.5s-1s)$. (c) Median SDR_{max} . (d) Median PFA.

CONCLUSIONS

This paper explores the engineering applications of SCEC BBP simulation (v17.3) for both code-based MCE_R design checks (ASCE 7-16) and multi-intensity performance-based assessments of tall buildings. Following the project of the SCEC Ground Motion Simulation Validation (GMSV) Technical Activity Group (Luco et al., 2017; Goulet et al., 2018), the seismic deaggregation, dominant earthquake sources, and simulated site-specific BBP records for three illustrative sites in San Francisco (SF), Los Angeles (LA), and San Bernardino (SB) were summarized. Comparable ground motion record suites were selected from the BBP and NGA-West databases. Two tall buildings, a 20-story frame and a 42-story shear wall, were modeled and analyzed at the three sites under comparable suites of selected BBP and NGA records. From the code-based MCE_R design check study, major findings are as follows.

- (1) Referring to the observations at the San Francisco and Los Angeles sites, if the average response spectra of the selected BBP and NGA record suites are closely fitted to the MCE_R target spectrum, the resulting average responses are also comparable. The benefit of utilizing BBP records is more apparent when using the conditional mean spectrum as the target spectrum, as recommended by the authors. This is because by explicitly simulating the dominant earthquake scenarios, BBP records represent more realistic spectral amplitudes and shapes. This implies that utilizing the BBP simulations can avoid excessive scaling of earthquake ground motions and its potential estimation bias in nonlinear response analysis. Based on these observations, it is suggested that the BBP seismograms can be utilized for code-based design checks.
- (2) At the Los Angeles and San Bernardino sites subjected to strong near-fault effects, the average structural responses under the BBP records are found to be sensitive to large drifts under pulse-like records. A relevant evaluation study for the SCEC CyberShake simulations (Teng and Baker, 2019) observed excessive polarization and pulse features in hybrid near-fault seismograms, which was reasoned to be caused by the strong coherence in some kinematic fault rupture models. This suggests that users should check the number of pulse-like records in the 11 selected ground motions and exercise judgement to check for and avoid including unrealistic near-fault seismograms in the record set.

The BBP simulations were also used in performance-based assessments of the two buildings, with major findings as follows.

- (1) Referring to the observation at the San Francisco and Los Angeles sites, if the NGA and BBP records are selected to match the same GCIM target (i.e., CS and duration distribution conditioning on $Sa(T_1)$) with

similar fitting qualities, the estimated structural response demand distributions and collapse risks are of no statistically significant difference. The BBP records offer the conceptual benefits of reduced need for scaling and better representation of the earthquake characteristics.

- (2) Referring to the observation at the Los Angeles site, when recorded local strong ground motion data are not available for the site, utilizing BBP seismograms helps avoid the potential estimation bias in structural response analysis resulting from larger estimates of spectral variations by ergodic ground motion models for a specific earthquake source. Moreover, referring to the observation in the Los Angeles site at the 2% in 200 years intensity level, where multiple earthquake sources contribute to the hazard, ground motion selection based on source-specific CS (Lin et al., 2013) is more desirable, as illustrated by site-specific reselection considerations that select ground motions individually for each major source following their relative contributions to the total hazard.
- (3) Referring to the observation at the San Bernardino site, the spectral shape of BBP near-fault records may deviate from the empirical GMPE spectrum at periods below 1s. This is attributed to the splicing of stochastic and deterministic components to capture high frequencies. Such deviations can be identified by the average spectral acceleration measure Sa_{avg} , calculated over the period range of 0.5s-1s. Given the positive correlation observed between the median $Sa_{avg}(0.5s-1s)$ and the median PFA , future validation studies are suggested to examine the $Sa_{avg}(0.5s-1s)$ of BBP near-fault records. With continued improvements, BBP simulations have the potential for providing pulse-like records for practical uses that are more representative of site-specific pulse effects for near-fault ground motions.

These conclusions are based on the observations in the numerical simulations of two archetype buildings. While results of the study are sensitive, in general, to the structural characteristics and modeling approach, the models used in this study are considered to be fairly representative of buildings with moment-resisting frames and shear walls designed in accordance with current building codes and practice. Further studies would be useful to consider (1) three dimensional structural analyses, (2) additional structural materials and system types, (3) earthquake simulations that incorporate three-dimensional velocity structures and local soil effects, and (4) earthquake simulations that directly simulate higher-frequency contents (i.e., higher than 1 Hz) and near-fault directivity features of ground motions.

FURTHER READING AND DATA AVAILABILITY

Readers can access (1) details about the ground motion selection and structural analysis results of this study in the digital appendix (url: <https://purl.stanford.edu/vd748js9648>), (2) an overview of the SCEC GMSV project (<https://www.scec.org/workshops/2018/gmsv>), (3) the BBP 3D seismograms created for the SCEC GMSV project at the DesignSafe data depot (<https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-1975>), and (4) the latest SCEC BBP software and source code (<https://github.com/SCECcode/bbp>).

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