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DATA PAPER
A Subset of CyberShake Ground-Motion Time Series for Response-History Analysis

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Abstract

This manuscript describes a subset of CyberShake numerically simulated ground motions that were selected and vetted for use in engineering response-history analyses. Ground motions were selected that have seismological properties and response spectra representative of conditions in the Los Angeles area, based on disaggregation of seismic hazard. Ground motions were selected from millions of available time series and were reviewed to confirm their suitability for response-history analysis. The processes used to select the time series, the characteristics of the resulting data, and the provided documentation are described in this manuscript. The resulting data and documentation are available electronically.

Keywords

CyberShake, Physics-Based Ground-Motion Simulations, Time Series, Response-History Analysis

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Introduction

Numerical 'physics-based' simulations of ground motions are an increasingly valuable resource for engineers, and they play a role in both ground-motion hazard analysis and response-history analysis. Provided that the simulation methods and parameters have been properly validated in ranges for which recorded data exist, they can provide insight into the scaling of ground motions with magnitude and distance or for rupture geometries not yet observed. One other advantage of simulations versus recorded ground-motion data is the essentially infinite amount of variations that can be produced for a wide range of rupture and site characteristics. Conversely, the massive amount of potential data and variations to choose from can make it difficult for a structural design team to quickly locate appropriate time series for analysis.

This Data Paper aims to address the issue by documenting a subset of time series selected from the CyberShake platform output. A small number of time series (i.e., 320 two-component horizontal ground motions) were selected from rupture scenarios of interest for engineering analysis in southern California. They were screened to have suitable response spectra and vetted to omit time series with unusual or potentially problematic characteristics. This paper describes the project's objectives and documents the process used to select the time series.

CyberShake is a Southern California Earthquake Center (SCEC) high-performance computing platform developed to conduct simulation-based seismic hazard analysis. It samples an earthquake rupture forecast (ERF) to generate earthquake ruptures, for which wave propagation is then computed (Graves et al. 2011; Jordan et al. 2018; SCECpedia 2020). The CyberShake products include ground-motion time series and intensity measures at selected sites on a closely spaced grid. The current implementation of CyberShake uses the Uniform California Earthquake Rupture Forecast 2 (UCERF2, Field et al. 2009) and samples over 400,000 ruptures from the model, focusing on Moment Magnitudes (M) of 6 and above, within 200 km of a site. Earthquake ruptures are described kinematically, with slip amplitude, direction, and timing across the fault specified based on models calibrated from inversions of past earthquake sources and dynamic rupture simulations (Graves and Pitarka 2015). The CyberShake platform uses reciprocity to compute wave propagation through Green strain tensors computed for three-dimensional (3D) velocity models of the Earth, which incorporate the effects of sedimentary basins and other features in the crust. Because these simulations reflect the physical processes associated with earthquake rupture and wave propagation, they and other similar approaches are often referred to as 'physics-based.' CyberShake Study 15.12 results used here also include stochastically simulated high-frequency (> 1 Hz) ground motion in addition to the deterministic low-frequency simulations described above. The high-frequency simulation uses a physically motivated but simplified model for wave propagation and scattering to generate theoretically consistent ground motion amplitudes at these frequencies, based in part on the model of Boore (1983). Because explicit wave propagation simulation at high frequencies would require source and crustal properties that are unknown, this stochastic approach is a viable method to obtain a more realistic ground motion across the full frequency range of interest. The resulting ground motions are expected to exhibit realistic features for frequencies that are of most interest for engineering analysis (up to about 20 Hz). The implementation of this hybrid approach follows that described in Graves and Pitarka (2010).

The region of interest for this study is the greater Los Angeles area (Figure 1). The 3D velocity model used for this CyberShake region (CVM-S4.26.M01) has been validated for the ground motions it produced by different teams of researchers using waveforms and various engineering metrics (e.g., Lee and Chen 2016; Small et al. 2017; Taborda et al. 2016). Simulations from the CyberShake platform (ruptures, velocity model, wave propagation) have been used previously for estimating response spectra for seismic design (Crouse and Jordan 2016; Crouse et al. 2018) and for response-history analysis and validation (Bijelić et al. 2019a,b; Teng and Baker 2019).

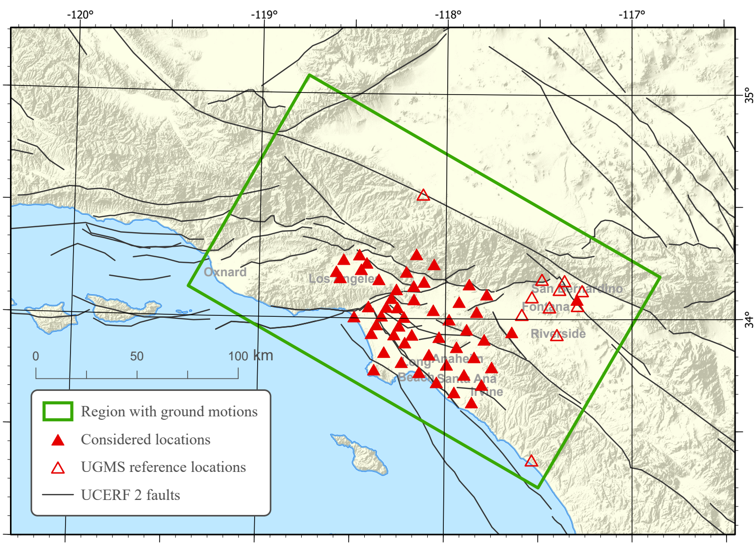

Figure 1. Map of the study area, showing the CyberShake simulation domain, the considered candidate locations and the earthquake sources (UCERF2 faults).

Ground-motion simulations can be used for several purposes in engineering analyses (Bradley et al. 2017), including response history analysis, supporting the development of empirically-calibrated Ground-Motion Models (GMMs), or hazard analysis to estimate ground shaking amplitudes or structural responses from future earthquakes. In particular, seismic hazard analysis can be advanced by utilizing simulations to supplement predictions from empirically-calibrated GMMs because simulations can be produced for areas with limited empirical data from ground motion recording typically used for hazard analysis (Dreger et al. 2015; Goulet et al. 2015). Simulations present an advantage over GMMs in that they produce complete time series, not only spectral response.

Hence, given a hazard analysis and target spectrum, simulated ground-motion time series can be used as inputs to a response-history analysis. To date, engineering analysis studies have found that the CyberShake ground motions generally have realistic features of engineering interest and that basin effects may, in some cases, produce greater structural demands than comparable recordings with no basin effects (Bijelić et al. 2019b). This motivates our desire to provide time series from this platform for engineers needing to consider such effects.

When performing ground-motion selection for this effort, we took the perspective of an engineering consultant looking to utilize ground motions for a design or assessment project in the Los Angeles area. In projects requiring time series for response-history analysis, a site-specific spectrum (or spectra) will be utilized, considering site conditions and other unique features of a given site (e.g. ASCE 2016; LATBSDC 2008; Moehle et al. 2017). Furthermore, future projects could take place at many locations. Hence, we did not define a single location or target spectrum for this project, and we determined that it would be best to select ground motions with a range of spectral amplitudes and shapes for that relatively large region. Most consultants are accustomed to simple interfaces to existing libraries of recorded ground motions and may find the SQL-based CyberShake interface challenging. Additionally, considering more than 159 million available two-component seismograms is much more complicated than selecting from amongst a few thousand recordings. These considerations were the primary motivation behind our work. By pre-screening and pre-vetting a manageable subset of ground motions, we add value to an engineering consultant who may not have prior experience reviewing ground-motion simulations and may need to justify the quality of the motions to a peer review panel and other members of the project team. The selected ground motions also supplement existing recorded datasets in a meaningful way as they span magnitude and distance ranges currently poorly represented. These ground motions also include the regional crustal effects expected in the Los Angeles area.

Ground-Motion Selection Approach

The process used to select the ground motions consisted of the following steps, which are described in the following subsections:

1. Specify candidate locations and site conditions of interest.
2. Perform hazard disaggregation for cases of interest to determine earthquake scenarios (i.e., magnitudes and distances) contributing most to hazard.
3. Select a small number of target earthquake scenarios based on disaggregation data and screen the CyberShake database to find simulations from those scenarios.
4. Generate target response spectra for each target earthquake scenario and select closely matching recordings from the screened database.
5. Review the identified time series.
6. Produce documentation.

Specify Candidate Locations and Site Conditions

We considered 52 locations in a Los Angeles region, as shown in Figure 1. These locations are a subset of the 63 reference locations previously used by the SCEC Utilization of Ground Motion Simulations (UGMS) committee (`https://data2.`

Table 1. Example disaggregation results for a location near downtown Los Angeles. Sources contributing more than 1% to exceedances of the $SA(1s)$ MCE_R amplitude are listed, along with their percent contribution, and mean values of magnitude and distance. Distance is defined as the closest distance to the rupture.

Source	Contribution [%]	Magnitude	Distance [km]
Elysian Park	30.9	6.9	5.4
Puente Hills	16.0	7.2	6.6
Newport-Inglewood	9.7	7.3	13.1
Compton	8.3	7.3	14.5
Background seismicity	6.8	6.4	8.6
Hollywood	4.7	7.3	8.3
San Andreas	3.0	8.1	55.5
Sierra Madre	2.7	7.7	19.9
San Vicente	1.2	6.7	6.3

`scec.org/ugms-mcerGM-tool_v18.4/`, Crouse et al. 2018), selected from the available 336 sites in CyberShake study 15.12. The subset includes locations where the U.S. Geological Survey (USGS) had previously performed disaggregations on a tightly-spaced grid (0.01 by 0.01 degree).

Perform Hazard Disaggregation

For each of the locations and site conditions, disaggregation was performed to identify the earthquake magnitudes and distances most likely to cause ground-motion amplitudes of engineering interest. Hazard and disaggregation calculations from the most recent USGS National Seismic Hazard Model (Petersen et al. 2020) were used for these evaluations. The ground-motion amplitudes of interest were pseudo-spectral acceleration (SA) values at risk-targeted Maximum Considered Earthquake (MCE_R) amplitudes, as computed for the 2020 NEHRP Recommended Seismic Provisions (Hamburger et al. 2017).

Disaggregation was initially performed at 22 spectral periods from 0 to 10 s and for eight of the site classes defined by the 2020 NEHRP Recommended Seismic Provisions. Based on an evaluation of those data, the analysis was simplified to consider two site condition values ($V_{S,30} = 365$ and 760 m/s), and four spectral periods (0.2, 1, 2, and 5 seconds), as those were seen to produce disaggregation results representative of the other conditions as well.

Each disaggregation calculation produced a list of fault sources that significantly contributed to the total hazard, with respective mean earthquake magnitudes and mean source-to-site distances. Table 1 shows sample results from a location in downtown Los Angeles (latitude = 34.05, longitude = -118.25), a $V_{S,30}$ of 365 m/s, and a spectral period of 1 second.

The magnitude and distance values for all locations, periods, and site conditions are shown in Figure 2. As expected, the MCE_R amplitudes for all cases result from large magnitude ruptures at small distances. In contrast, the vast majority of available ground-motion recordings are from smaller magnitude and larger source-site distances.

To illustrate, the magnitude and distance values of recordings available in the large NGA-West2 ground-motion database (Ancheta et al. 2014) are also shown in Figure 2. The relative sparsity of available recordings with target magnitude and distance values motivates the collection of the simulations described herein.

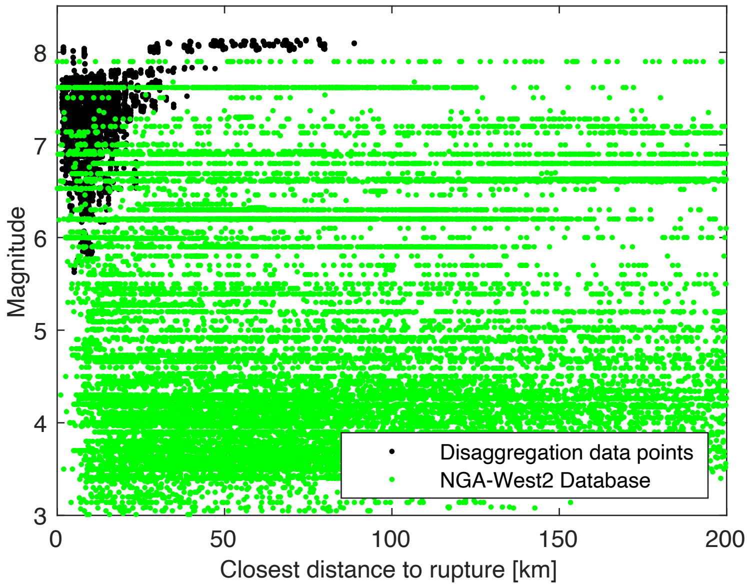

Figure 2. Magnitude and distance values of disaggregation targets from this study, and of ground motions in the NGA-West2 database (Ancheta et al. 2014).

Figure 3 shows disaggregation results for particular site conditions and spectral periods to illustrate key patterns in the results. To account for the fact that each point on the plots has a different percent contribution, we performed a kernel-smoothed estimate of the total contributions associated with each magnitude and distance value. At each magnitude and distance value, all points within ± 0.2 magnitude units and ± 5 km were collected, and the sum of the percent contributions was computed. Contours of these resulting estimates are shown in the figure to indicate the magnitude and distance values most likely to be contributing to hazard.

Several observations can be made from Figure 3. The similarity of Figure 3a and 3b, which consider the same periods but differing site conditions, confirms that site conditions have a negligible impact on the disaggregation result of interest. Given this stable disaggregation result, we use the same rupture scenarios for both site conditions. A comparison of Figure 3c and d, which have the same site conditions but consider short- and long-period SA values, shows that the short-period SA values are mostly caused by moderate-magnitude ($5.5 < M < 7.5$) earthquakes at distances within 20 km.

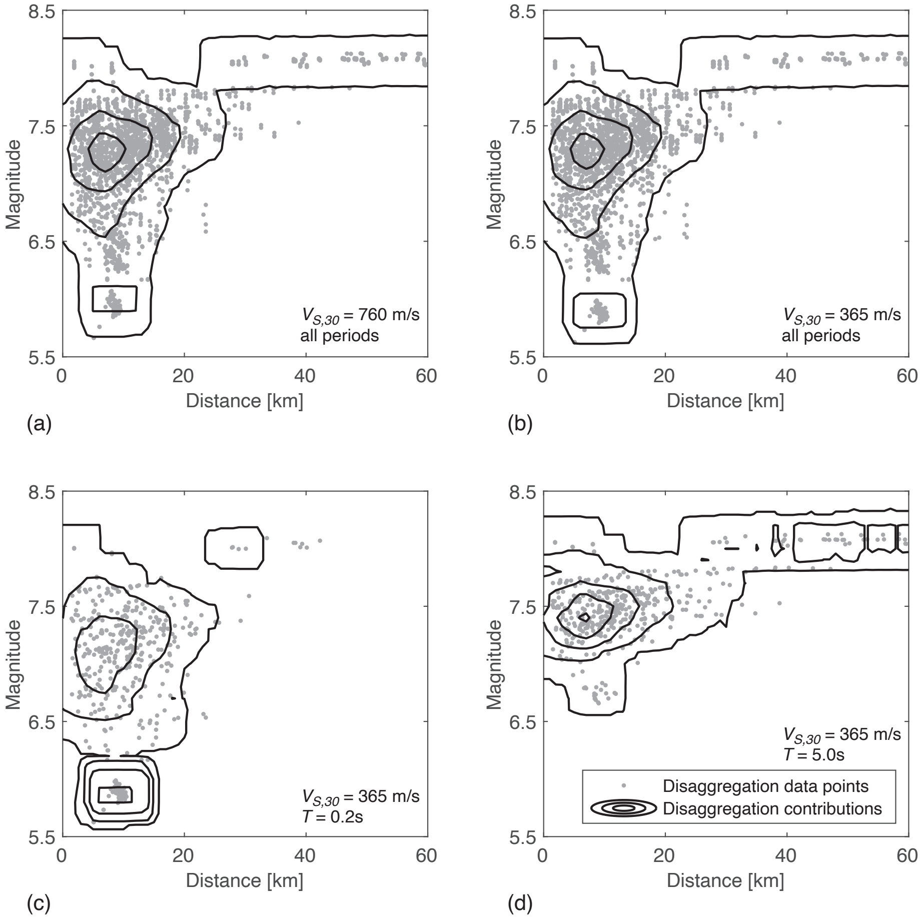

Figure 3. Disaggregation values for subsets of cases. Black lines show contours from kernel smoothing (values within ± 0.2 magnitude units and ± 5 km), to indicate magnitudes and distances with highest disaggregation contributions. (a) $V_{S,30} =$ 760 m/s, all periods. (b) $V_{S,30} =$ 365 m/s, all periods. (c) $V_{S,30} =$ 365 m/s, $T =$0.2s. (d) $V_{S,30} =$ 365 m/s, $T =$5.0s.

In contrast, longer-period SA values are more likely to be caused by larger-magnitude and more distant ruptures.

Select Rupture Scenarios and Screen Database

Because the selected ground motions are intended to be relevant for a range of locations, site conditions, and spectral periods, the disaggregation data were pooled and used to select representative rupture scenarios (Figure 4). We focused on scenarios that appear frequently in the disaggregation data and where few recordings are available. Figure 4 shows the selected target scenarios. Magnitude 8 ruptures at distances of 5 and 40 km were selected to represent large magnitude events that could produce expected long-duration shaking. Magnitude 7.3 and 6.5 ruptures at distances of 8 km were selected due to the significant contribution they make to MCE_R hazard. Magnitude 6 ruptures at 10 km also make a significant contribution to hazard, but they were not considered further as many suitable ground-motion recordings exist for this case (Figure 2).

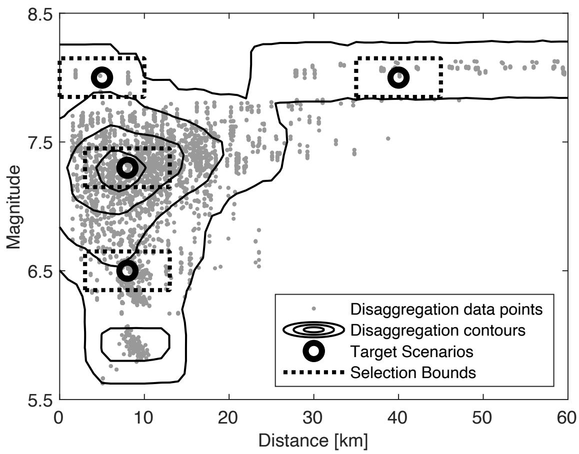

Figure 4. Disaggregation values for all cases (grey dots), contours from kernel smoothing (black lines), target earthquake scenarios (black circles), and bounds around the scenarios for selection (dotted black lines).

For each of these four rupture scenarios, and for each of the two site conditions, we search the CyberShake database for time series associated with these conditions. Because our selected rupture scenarios and site conditions are intended to represent a range of similar conditions rather than a precise magnitude, distance, and $V_{S,30}$, a range of acceptable values were considered for each case. The ranges deemed to produce suitable numbers of ground motions and cover the rupture conditions of interest were $M \pm 0.15$, $R \pm 5$ km, and $V_{S,30} \pm 20$ m/s. Figure 4 shows the bounds of these selection criteria around each of the four scenarios. The ranges of considered parameter values are quite narrow compared to typical ranges used in selection of recorded ground motions because of the large number of available simulations as discussed in the following paragraph. The magnitude range is one exception—this is somewhat wider because the simulated magnitudes are discritized at intervals of 0.1, so a wider range is needed to include these discrete values.

The number of CyberShake time series matching these selected ranges are shown in Table 2. In contrast to databases of recorded ground motions, where there are often few if any suitable recordings, there are tens of thousands of available simulated time series for each rupture scenario of interest. Also in contrast to databases of recorded ground motions, the most time series are available for the largest-magnitude scenarios. This is

Table 2. Number of available Cybershake time series for each of the eight scenarios of interest. The left three columns specify the scenario, the fourth column indicates the number of ruptures and corresponding sites matching the scenario, and the fifth column indicates the number of available time series.

Magnitude	Distance (km)	$V_{S,30}$ (m/s)	# of site-rupture pairs	# of ground motions
8.0	5	760	5,553	2,075,381
8.0	5	365	2,444	904,177
8.0	40	760	2,031	725,068
8.0	40	365	890	311,188
7.3	8	760	4,847	511,899
7.3	8	365	2,166	233,708
6.5	8	760	1,904	33,487
6.5	8	365	943	16,445

because the CyberShake platform is designed to produce more rupture realizations for ruptures with a large surface area, which is correlated with magnitude.

Generate Target Response Spectra and Select Matching Motions

Simply constraining the rupture and site characteristics for ground-motion selection leaves millions of available candidate time series, as seen in Table 2. That is many more than are needed for engineering evaluations considered by this project. To further reduce the selected set of motions, while ensuring that the chosen motions have ‘useful’ levels of shaking amplitude, a spectral-target-based selection approach was utilized. The use of a spectrum for this step is a means to an end to reduce the large dataset and to eliminate time series that diverge significantly from a typical spectral shape.

The procedure used at this step is illustrated in Figure 5. For each rupture scenario, the means, standard deviations, and period-to-period correlations of resulting (log) response spectra are computed from empirical ground-motion models (Baker and Jayaram 2008; Boore et al. 2014). Then samples of response spectra are generated using a Monte Carlo simulation, assuming that the log response spectra have a multivariate normal distribution with means, standard deviations, and correlations as computed in the previous step (from the empirical datasets). Finally, each of the sampled response spectra is compared to the available ground motions’ response spectra, and the ground motion with the closest match is selected. This process follows the ‘unconditional selection’ algorithm that has been previously applied to select ground motions from databases of recordings (Baker et al. 2011).

The proposed procedure has several advantages for this application. First, the process of matching to spectra ensures that the amplitudes of the selected simulations are consistent with empirical data; hence, any simulations with unexpected amplitudes are not selected. There is a broader academic question as to whether simulated amplitudes that meaningfully differ from empirical models indicate a deficiency in empirical models. For this application, however, we are assuming that the target amplitudes are coming from other sources and that the simulations are not being utilized to question those amplitudes. Second, the process results in a set of ground motions whose spectra cover a range of

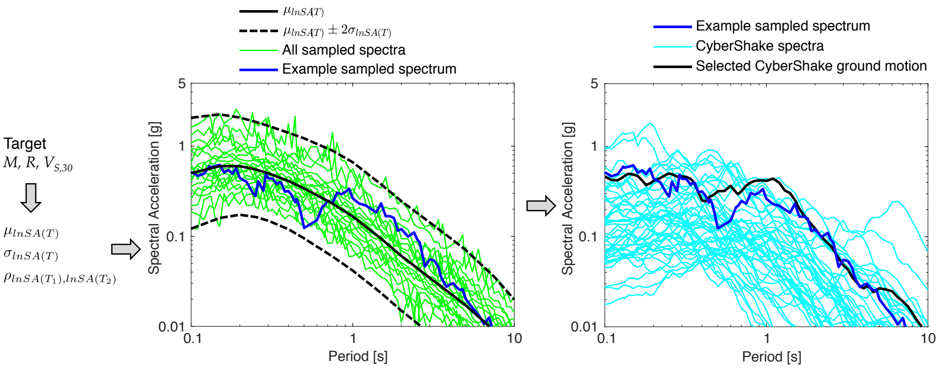

Figure 5. Schematic illustration of the ground-motion selection process. We first specify a target scenario and compute the means, standard deviations and correlations of $lnSA$ (left); we then sample response spectra from the resulting distribution (middle); finally, we compare each sampled response spectrum to the CyberShake spectra and select the closest match (right).

plausible amplitudes and shapes (e.g., Figure 6). We have not pre-assumed a specific design spectrum, so a user with an arbitrary spectrum can find suitable ground motions in this set. Third, the process can produce an arbitrary number of selected motions, simply by varying the number of Monte Carlo samples.

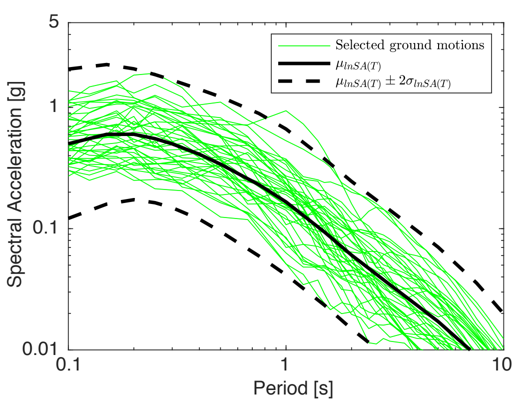

Figure 6. Response spectra of CyberShake ground motions selected to match the $M = 6.5$, distance = 8 km, $V_{S,30} = 760$ m/s scenario. Mean and mean $\pm$ 2 standard deviation predictions of $lnSA$ for that scenario are superimposed for reference.

For this particular application, the following choices were made when implementing the sampling and selection algorithm.

- The models of Boore et al. (2014) and Baker and Jayaram (2008) were used to generate the target mean, standard deviation, and correlation values for the Monte Carlo simulations.
- Thirty spectral acceleration periods between 0.1 and 10 seconds were considered when sampling spectra and comparing simulations to these samples. The periods were those for which spectral values are tabulated in the CyberShake database. While longer periods are presumably of greatest interest given the intended application to tall buildings, and given that the simulations produce the most insight at long periods, all periods were considered at this step because it was not difficult to obtain time series with appropriate spectra over the full period range.
- Forty Monte Carlo samples of response spectra were produced for each of the eight scenarios, and one CyberShake ground motion was selected to match each sample.
- RotD50 response spectra were used for both the target spectra sampling and the CyberShake simulation spectra. This is the median spectral amplitude over all possible horizontal orientations of the ground motion (Boore 2010). (The RotD100 spectra of the selected ground motion motions are also consistent with anticipated spectral amplitudes, and either metric could have been used at this step without significant impact on the results.)
- The match between a sampled target spectrum and a particular simulation was measured using the sum of squared errors between the log sampled spectrum and log CyberShake spectrum, over the 30 periods of interest.
- No amplitude scaling of the ground motions was permitted.
- Selected ground motions consist of the two horizontal components for which the RotD50 values were screened. Vertical ground motions are not produced in this simulation platform, and so are not provided.

Example response spectra of ground motions selected by this process are shown in Figure 6. We note that the variability of these selected spectra is slightly lower than the variability of the initial target response spectra. This is partly due to the spectral shapes of ground motions available in the CyberShake database, and these differences are visually exacerbated in Figure 6 because spectral values are plotted for a relatively small number of periods. This is acceptable, as the goal is not to perfectly replicate the distribution of spectral values predicted by a ground-motion model, but rather to provide the engineering community with ground motions exhibiting reasonable and defensible amplitudes and a range of spectral shapes. Trial efforts to select ground motions from the developed subset indicates that it is feasible to select motions matching a range of conditional mean spectral shapes and other potential target spectra; hence, the results were deemed satisfactory.

Figure 7 compares response spectral values of the selected ground motions and the NGA West2 motions. Figure 7a shows response spectra of a random sample of 100 ground motions from each set. Figure 7b shows the complete sets of ground motions, plotted for two spectral acceleration periods. The figure illustrates that the selected motions are comparably high in amplitude to (but not above) the strongest motions in the NGA West2 database, as anticipated from Figure 2.

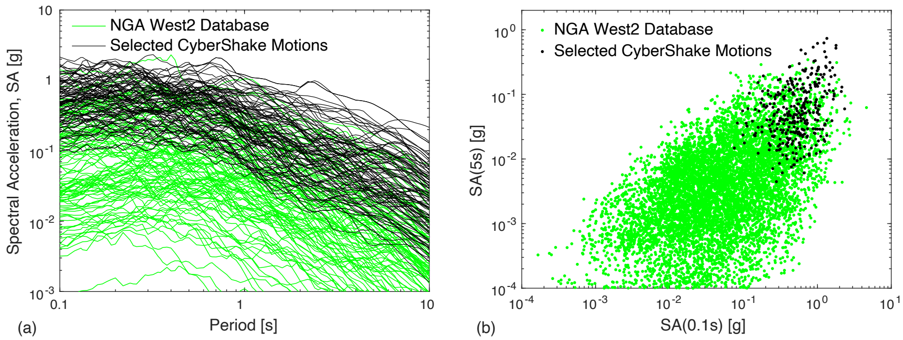

Figure 7. (a) Response spectra of 100 randomly selected ground motions with $M > 5$ from the NGA West2 database, and 100 randomly selected ground motions from the curated set of CyberShake ground motions. (b) SA(0.1s) and SA(5s) values from the PEER NGA West2 database and the selected CyberShake ground motions.

Review time series

The process and results described above were subject to several stages of review during the project. The candidate locations, disaggregation parameters and results, and selected target earthquake scenarios were presented to the SCEC Ground Motion Simulation Validation (GMSV) committee for comment and feedback. Once the target scenarios were finalized, the ground-motion selection process and selected ground motions were presented to the GMSV committee and some members of the SCEC UGMS committee, for further comment. Reviewed materials included plots of time series, response spectra, and metadata for selected motions. These reviews (along with many iterations of internal review by the authors), resulted in refinements to the analysis process, adjustments to the selected set of ground motions, and identification of key metrics to document.

These reviews were intended to maximize the value of the final ground motion set and also to encourage questions and potential objections that might arise if these data were to be used in an engineering assessment. Based on the scrutiny that the ground motions have received, and the lack of remaining concerns, we believe that these ground motions would be suitable for use in response-history analysis applications as a supplement to or in place of recordings.

Produce Documentation and Repository

The data repository is available at `https://doi.org/10.5281/zenodo.3875541` (Baker et al. 2020a). The repository contains a Comma-Separated Values (CSV) file with the following metadata fields for each selected ground motion:

- Station name and ID
- Site $V_{S,30}$ (average shear wave velocity in the top 30m)
- Shortest distance to the rupture

- Earthquake source name
- Earthquake magnitude
- An indicator of the presence of a velocity pulse, and the period of that pulse if it is present (Shahi and Baker 2014)
- 5-75% significant duration
- Hypocenter latitude
- Hypocenter longitude
- Hypocenter depth
- Depth to top of rupture
- 5%-damped RotD50 response spectra at 30 periods between 0.1 and 10 seconds
- File names for each component of the time series

Numerical data for each component of the time series are provided as individual text files. Finally, plots of response spectra and time series (acceleration, velocity, displacement) are provided for each ground motion component as individual Portable Network Graphic (PNG) files, and all of the figures are compiled into a summary Portable Document Format (PDF) report. Figure 8 shows example plots for one selected ground motion. The intended use of this repository is that a user can search the metadata file to find ground motions satisfying the desired selection criteria and then extract the corresponding time series files for further analysis.

The data are also loaded into a ground-motion selection tool at `https://github.com/bakerjw/CS_Selection` (Baker et al. 2020b), so that the ground motions can easily be searched using the same approach as is available for searching libraries of recordings (Baker and Lee 2018).

Conclusions

This paper summarizes the contents of a selected set of CyberShake ground motions, which were developed to facilitate the response-history analysis of structures. The CyberShake ground-motion database provides a library of millions of numerically simulated ground motions from large shallow crustal ruptures relevant for engineering analysis in Southern California. The CyberShake simulations also consider several physical processes of interest in Southern California, such as the effects of rupture directivity and sedimentary basins on shaking time series.

To utilize this extensive library for engineering analysis purposes, we developed a procedure to screen and select a small number of relevant ground motions. We performed seismic hazard disaggregation analysis for a number of Southern California locations to determine the earthquake ruptures that contribute most significantly to hazard. We then selected four target rupture scenarios and two near-surface soil conditions for each. For each scenario, we computed response spectra means, variances, and correlations from an empirical GMM and then generated corresponding Monte Carlo samples of response spectra. Those samples were used as targets to find CyberShake ground motions with comparable response spectra. This procedure resulted in a set of 320 ground motions (selected from a database of millions) that come from earthquake ruptures of interest to

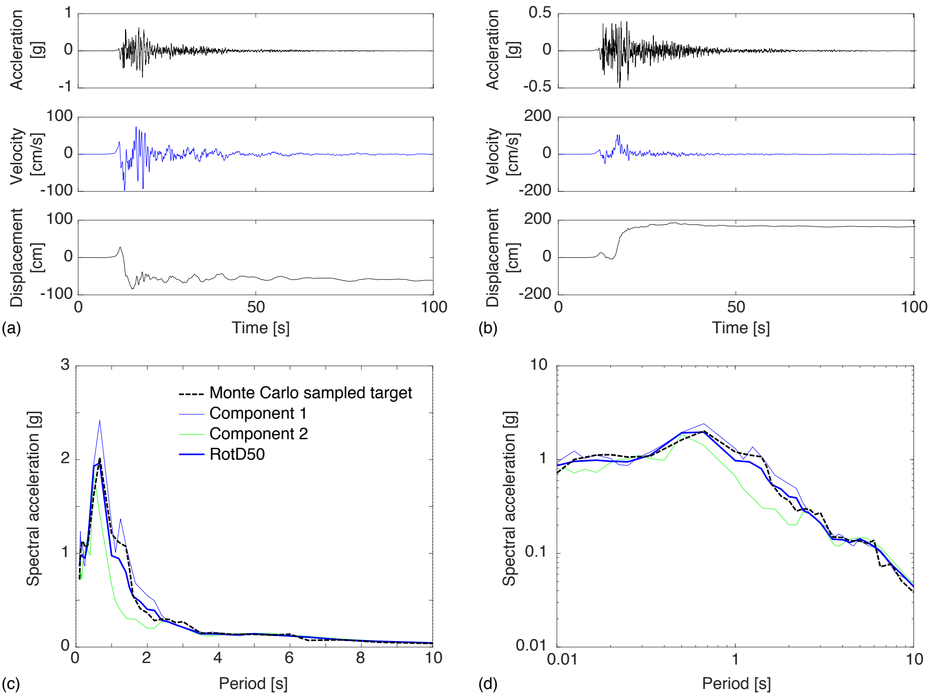

Figure 8. Example time series and spectra plots for a selected ground motion (a $M = 7.85$ San Andreas rupture recorded at a distance of 0.3 km with $V_{S,30} = 748$ m/s). (a) Component 1 acceleration, velocity and displacement. (b) Component 2 acceleration, velocity and displacement. (c) Response spectra in linear scale. (d) Response spectra in log scale.

engineers and that have realistic and defensible ground-motion amplitudes and spectral shapes.

The resulting selected ground motions have also been reviewed to check for anomalous features or characteristics that might make them questionable. We believe that the resulting set of ground motions are appropriate for use in response-history analysis of structures and that the pre-screening and review make the dataset more practical for engineers than the complete original database. The process utilized here can be replicated in the future, as ground-motion simulation databases become increasingly large, necessitating procedures to screen and select appropriate subsets of ground motions.

Acknowledgements

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