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Evaluation of the Impact of CyberShake on Risk Assessments for Distributed Infrastructure Systems

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Summary

Presently empirical ground motion models (GMMs) are ubiquitously used to quantify the spatially correlated ground motion hazard in seismic risk assessments for spatially distributed systems. One current weakness of such empirical GMMs is that they are typically developed from global ground motion datasets. They represent “average” source, path attenuation, and site response characteristics of global earthquakes, and are associated with large variability components that reflect a variety of crustal structures and conditions. The average ground motions in a specific region are often different from those from the global average and are expected to exhibit lower variability. Such differences in median and variability can lead to poorly centered and wider than necessary distributions of the risk metrics. The SCEC CyberShake platform was designed to address the need for regional assessment of ground motions with physics-based earthquake simulations. Provided that the simulations have been properly validated, they should, in theory, include the source, path, and site effects of a specific region.

We build on a recent comprehensive probabilistic seismic risk analysis (PSRA) study of the underground water pipeline network for the City of Los Angeles, where the system-level performance (measured by the expected number of pipeline repairs, repair cost, and repair time) was established as a function of exceedance probability based on a large set of earthquake simulations using empirical GMMs. By repeating this study using the events and simulations from CyberShake15.12, we explore the impact of region-specific simulations on seismic risk assessments of distributed infrastructure. This work also serves as a proof-of-concept and is expected to provide guidance to the research and PSRA user communities.

We have successfully utilized the CyberShake15.12 and empirical GMMs as hazard inputs to conduct the system-level risk analysis for the transmission (trunk) line system. The total length of the Los Angeles Department of Water and Power (LADWP)’s trunk line network is about 400 miles and it covers a wide geographic area. The system-level risks computed from CyberShake15.12 simulations and empirical GMMs were found to be similar for shorter return periods (< 100-year) but show significant differences in longer return periods. Specifically, system-level risk computed from CyberShake is about 26% lower than that from GMMs at 500-year return period, and about 41% lower at 2,475-year return period, respectively.

In assessing the probabilistic system-level risks of a spatially distributed system, three ground motion characteristics play an essential role in characterizing the seismic hazard inputs: ground motion median, variability, and spatial correlation. Based on the findings from this study, we recommend that a careful examination of these regional ground motion characteristics of CyberShake simulation and empirical GMM methods to understand their impacts on the risk estimates of a distributed system.

Technical Approaches

General Approach

Figure 1 shows the map of the transmission (or trunk lines, pipelines with 24-inch or larger diameters) and distribution lines (pipelines less than 24-inch diameter) of the Los Angeles Department of Water and Power (LADWP)'s water pipeline network. The length of pipelines reaches more than 7,000 miles and covers a wide geographical area. As measured by length, approximately 93.1% of the pipes are associated with the distribution system, about 5.2% of pipes are trunk lines.

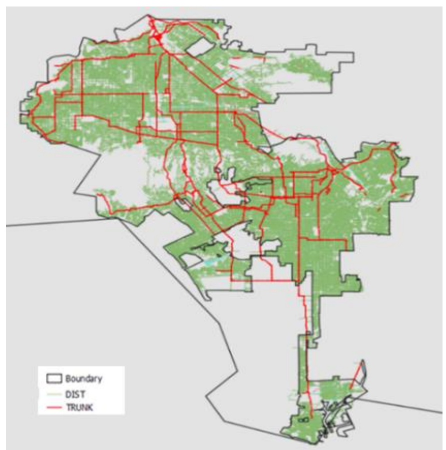


Figure 1. LADWP's water transmission and distribution pipeline systems

The analytical procedure for assessing system-level probabilistic seismic risks of the LADWP's water pipelines in Lee et al. (2019) is illustrated in Figure 2.

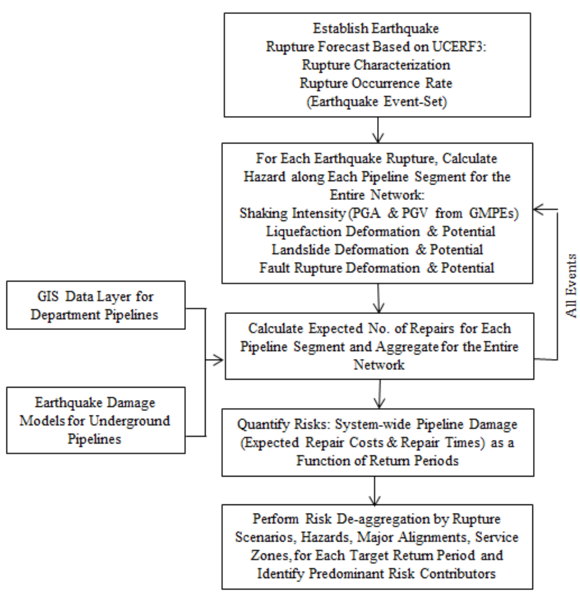


Figure 2 - System-level risk calculation procedure for the water pipeline network

The stochastic earthquake catalog, or “event set,” adapted the Uniform California Earthquake Rupture Forecast Version 3 (UCERF3) (Field et al., 2014) source model using a Robust Simulation approach (Lee et al., 2018). The approach comprehensively captures both epistemic and aleatory uncertainty in seismic hazard models through Monte Carlo simulations. The four NGA West2 GMMs, i.e., Abrahamson and others (2014), Boore and others (2014), Campbell & Bozorgnia (2014), and Chiou and Youngs (2014), were utilized to produce the ground motion intensity maps for each earthquake simulation in the event set. The between-event and with-event variabilities of ground motion uncertainty are treated as independent random variables, respectively. The between-event term was randomly sampled to reflect event-wide correlation of ground motion (i.e., systematically higher or lower intensities than predicted medians), while the within-event term was modeled to capture spatial correlation of ground motion for sites that are closely located using the empirical correlation model developed by Loth and Baker (2013). The damageability of water pipelines under ground shaking and ground failure was characterized using empirical fragility models developed by Honegger and Eguchi (1992), where the expected number of repairs of pipelines and joints per unit length is modeled as a function of peak ground velocity (PGV). The pipeline damageability is also characterized by pipe material, joint type, pipe size (diameter), age, and other characteristics of the pipelines. The cost and time to repair a damaged pipe were estimated based on data from past earthquakes and models provided by LADWP. In this study, we focus on the impact of the CyberShake model on pipeline seismic risks from ground shaking only. Future studies may extend to the impact from ground failure, which is also crucial to seismic performances of lifeline infrastructure.

Intensity Measure (IM)

The pipeline fragility function typically describes the pipe repair rate as a function of PGV. The CyberShakke15.12, however, has not computed PGV directly from the simulated ground motion time histories. For this study, PGV (centimeters per second) is inferred from spectral acceleration at 1 second (SA_1, units of g). The formula used is documented in the HAZUS method (FEMA, 2013), listed as follow:

$$PGV = \left(\frac{981.5}{2\pi} \times SA_1\right)/1.65$$

Although the PGV values can be calculated directly from the NGA West 2 GMMs, to compare the risk results on an equal basis, we use the same method to derive the PGV values from GMMs.

Stochastic Event Set

Up to now, the SCEC has developed the full CyberShake database for UCERF2 ruptures from the CyberShake Study 5.12 (https://strike.scec.org/scecpedia/CyberShake_Study_15.12). For a meaningful comparison of the impact of CyberShake models, it is desirable that the same set of earthquake ruptures are utilized, so that system-level risk outcomes using CyberShake simulations and empirical GMMs can be contrasted and compared. To achieve this, we develop a stochastic event set that adapts the UCERF2 ruptures for which the CyberShake simulations have been performed, using the approach as described in Lee et al. (2018). Specifically, we conduct a 500,000-year window of earthquake simulations to select the ruptures for system risk analysis. A rupture is randomly selected based on its probability of occurrence. For each rupture selected in the event set, ground motion intensities from CyberShake model are then obtained from the CyberShake15.12 database and those from empirical GMMs are calculated in this project.

Spatial Interpolation of Ground Shaking Intensities

Due to the high computational demand, CyberShake simulations have been conducted for a grid of sites that has a distance spacing on the order of 10 kilometers – with a limited number of extra sites placed in the Los Angeles basin area. Figure 3 shows the map of the sites where full-time series have been computed on specified soil conditions.

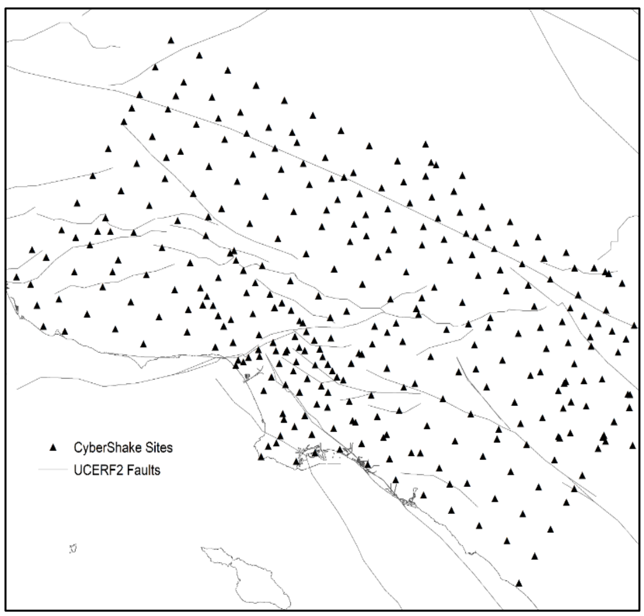


Figure 3 – CyberShake stations where full-time series have been computed

The sites are relatively sparse concerning potential ground motion variations between the stations for a dense pipeline network. Therefore, in this study, shaking intensities for locations between CyberShake sites are interpolated to better capture the spatial distribution of ground shaking. The algorithm that is used for spatial ground motion interpolation was developed and provided by Kevin Milner at USC. The procedure is described as follows:

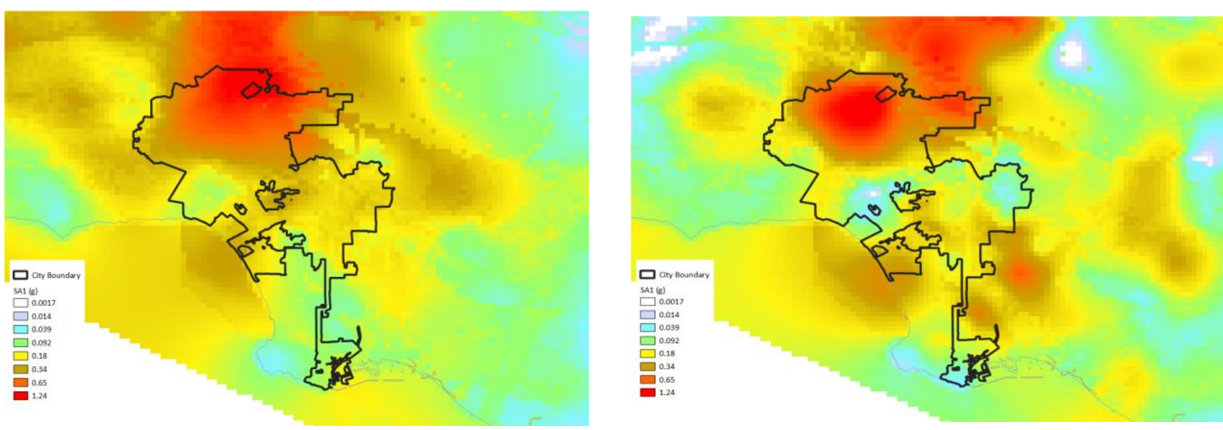
1) Compute high resolution (0.01 degree spacing) GMM basemap (median IM), and basin depth parameters from the velocity model used in the CyberShake study
2) At each CyberShake site, take difference: CyberShake and GMM, respectively
3) Interpolate those differences across the region at the basemap.
4) Add the interpolated differences back to the basemap

Note that ground motion variability in CyberShake model is represented through multiple realizations of source parameters (such as hypocentral locations and slip distribution). In computing a GMM intensity map for the same rupture scenario, we use the same GMM basemap computed for CyberShake intensity interpolation, considering both the between-event and within-event uncertainty in empirical GMMs are treated as random variables. This reflects another important difference between the empirical GMM approach and the CyberShake model in modeling regional seismic hazard. The same as in Lee et al. (2019), we model the local spatial correlation of ground motion resulting from the within-event term using Loth and Baker (2013). With the two sets of ground motions, we then calculate system-level risks of the pipeline network using the same pipeline damageability model developed in Lee et al. (2019), respectively.

Results

Scenario Intensity Map Examples

As an example, Figure 4 shows the scenario ground motion intensity (SA1) maps for a magnitude 6.95 event on the Sierra Madre (San Fernando) fault. The left shows the intensity map from CyberShake simulations, while the right shows the map calculated using GMM model. Both show realistic ground motion patterns.

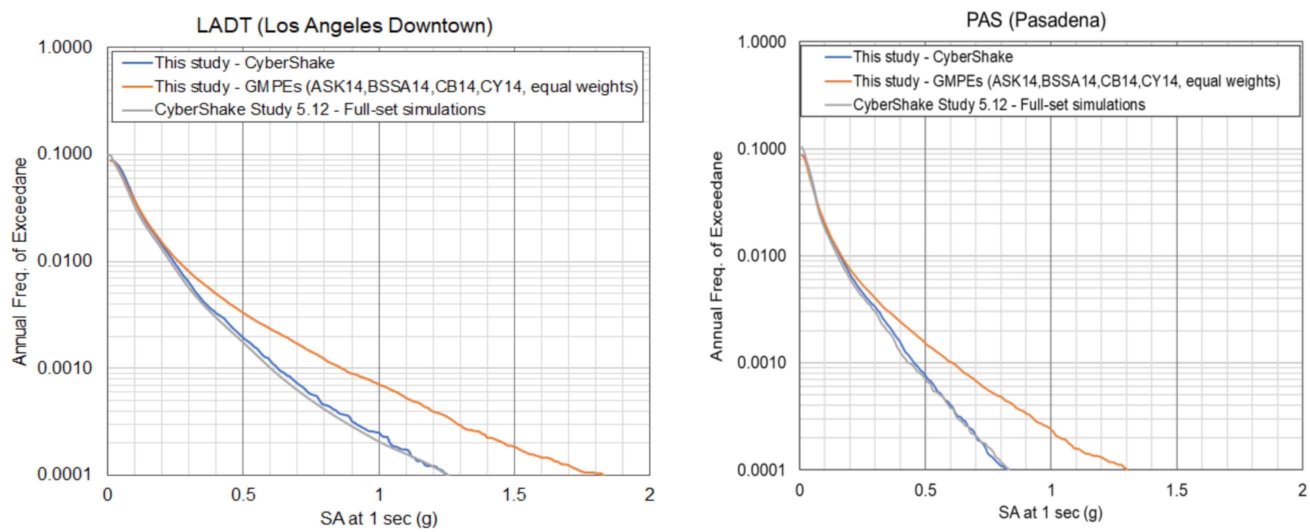


(a) (b)

Figure 4. An example of scenario ground motion intensity maps from CyberShake 15.12 simulation and GMM, respectively, (a) - CyberShake, and (b) - GMMs

Probabilistic Hazard Curves

We compare the probabilistic ground motion hazard curves computed using the stochastic event set constructed in this study for CyberShake15.12 and GMMs. We selected two sites: LADT (Los Angeles Downtown) and PAS (Pasadena), respectively, that SCEC has computed the probabilistic hazard curve using the full CyberShake simulations. The results are shown in Figure 5. As can be seen, the hazard curves calculated using the stochastic event set follow those that were calculated using the full set of CyberShake simulations closely. The hazard curves that are calculated using GMMs are similar to those of CyberShake for a return period shorter than about 100 years. For longer return periods, however, they show significant differences. For instance, for the LADT site, the ground motion hazard from GMMs is about 28%, 40%, and 47% higher at 0.4%, 0.2%, and 0.01% annual frequency of exceedance, respectively, or corresponding 250-, 500-, and 10,000-year return period.



(a) (b)

Figure 5. Comparison of probabilistic ground motion hazard curves calculated from CyberShakke15.12 (blue) and GMMs (orange) using the stochastic event set constructed in this study for two sites: (a) LADT and (b) PAS. Also shown are the hazard curves calculated using the full set of CyberShake15.12 simulations (grey).

System-level Risks

The pipeline system-level risk analyses were conducted for trunk lines for ground shaking using the CyberShake simulations and the NGA-West2 empirical GMMs, respectively. The system-level risk curves, where the expected number of repairs, repair cost, and repair time are expressed as a function of return period, were calculated and plotted in Figures 6 and 7. The expected number of pipe repairs for return periods of 100-, 500-, 2,500- and 10,000-years are also summarized in Table 1.

Figure 6 shows that the expected number of pipe repairs computed from CyberShake simulations and empirical GMMs are similar for relatively short return periods (< 100-year). However, they show significant differences for longer return periods. Specifically, at a 500-year return period, the expected number of pipe repairs calculated from CyberShake is about 26% lower than that computed from empirical GMMs. At a 2,475-year return period, the value is about 41% lower. The reduction of risk estimates using CyberShake simulations is substantial.

Figure 7 shows the estimated repair cost and repair time as a function of return period, calculated for CyberShake and empirical GMMs, respectively. The reductions in repair cost and repair time from CyberShake simulations are generally similar to those of the expected number of pipe repairs.

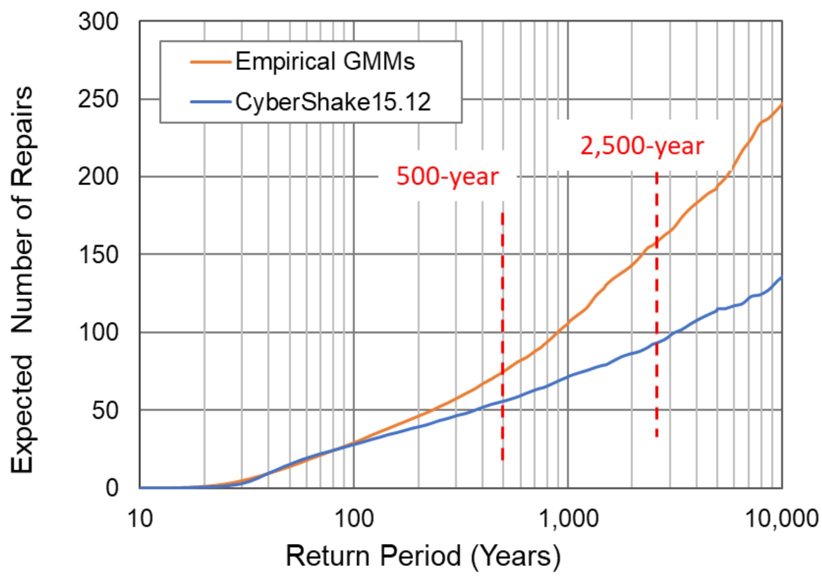
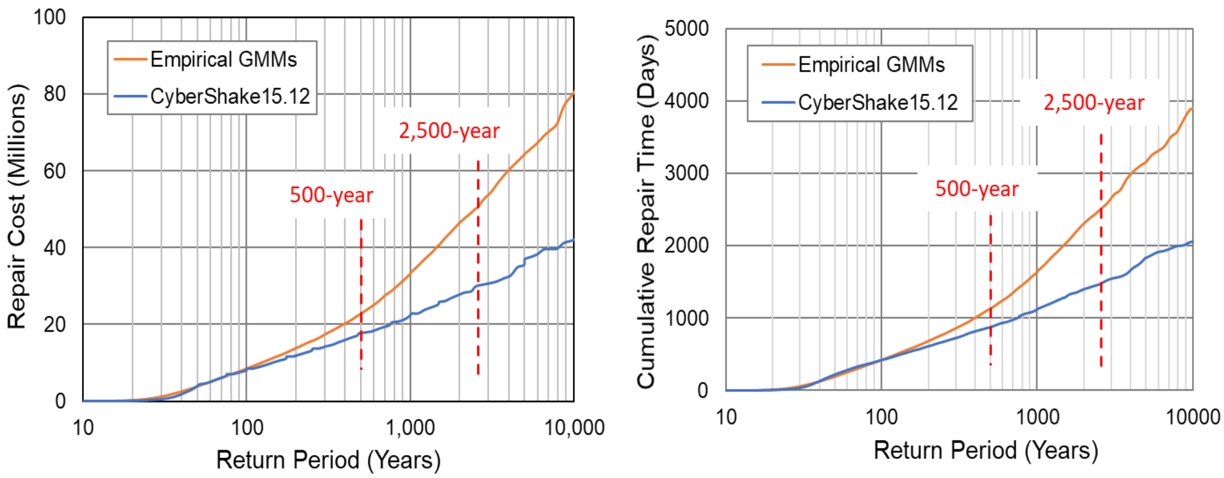


Figure 6. Expected number of repairs as a function of return periods calculated from CyberShake simulations and NGA-West2 empirical GMMs, respectively. The expected number of pipe repairs computed from CyberShake simulations and empirical GMMs are similar for relatively short return periods (< 100-year). However, they show significant differences for longer return periods. At a 500-year return period, the expected number of pipe repairs calculated from CyberShake is about 26% lower than that computed from empirical GMMs. At a 2,475-year return period, the value is about 41% lower.

Table 1. Expected Repair Costs and Repair Times

Return Period (Years)	Expected Number of Repairs		
	CyberShake (CS)	Empirical GMMs (GMM)	CS/GMM Ratio
100	28	29	0.97
500	56	76	0.74
2,500	92	156	0.59
10,000	125	246	0.51



(a) (b)

Figure 7. Pipe repair cost and repair time as a function of return periods calculated from CyberShake simulations and NGA-West2 empirical GMMs, respectively. (a) Repair cost, (b) cumulative repair time (assuming a single repair team).

Conclusions

As the first probabilistic hazard model using physics-based earthquake simulations, the CyberShake platform has been increasingly applied to test risk assessment at a single site for performance-based engineering. While the benefits of incorporating a physics-based understanding of earthquakes in PSHA modeling through models of rupture mechanics, wave propagation, and regional geologic structure have been widely recognized, the research on the use of a physics-based simulation technique for seismic risk assessment of spatially distributed infrastructure, however, has been limited.

The results of this study showed that seismic risk outcomes developed from physics-based earthquake simulations for spatially distributed systems can differ substantially from those obtained from conventional approaches utilizing empirical GMMs. These differences can have significant implications on public policies concerning seismic risks and on estimates of resources needed for agencies to adequately plan and mitigate the risks to meet the system resilience criteria.

In characterizing regional ground motion hazards, the physics-based earthquake simulations and conventional empirical GMMs differ in three main ground motion characteristics:

- Median attenuation from source to sites
- Ground motion variability
- Spatial correlation

All of these characteristics have significant influences on the risk estimate of a spatially distributed system. To further understand the causes of the differences in the resultant risk outcomes, it is crucial to quantify and compare the characteristics of these ground motion model components and their distinct impacts on the prediction of spatially correlated ground motions and corresponding risks. We plan to further investigate these issues, notably the role of variability and spatial correlation on these preliminary results. The critical step this research has made is the definition of new ways to compare results from otherwise different PSHA models. CyberShake produces a finite set of simulations (although it consists of over 580,000 time-series), with each scenario having a variable number of source variants. The workflows and rules we developed for comparisons with the traditional GMM-based approach will be useful for further studies.

Acknowledgments

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