CONTRASTING CYBERSHAKE SIMULATIONS AND CONVENTIONAL HAZARD ANALYSIS TO ASSESS COLLAPSE RISK OF TALL BUILDINGS IN THE LOS ANGELES BASIN

N. Bijelić¹, T. Lin² and G. G. Deierlein³

ABSTRACT

Limited data on strong earthquakes and their effect on structures poses one of the main challenges of making reliable risk assessments of tall buildings. For instance, while the collapse safety of tall buildings is likely controlled by large magnitude earthquakes with long durations and low-frequency content, there are few available recorded ground motions to evaluate these issues. The influence of geologic basins on amplifying ground motion effects raises additional questions. Absent recorded motions from past large magnitude earthquakes, physics-based ground motion simulations provide an attractive alternative. This paper examines collapse performance of an archetype tall building at sites in the Los Angeles basin utilizing ground motions simulated as part of the Southern California Earthquake Center’s CyberShake project. The collapse risks of an archetype 20-story tall building are obtained using large datasets (~500,000 ground motions per site) of unscaled, site-specific simulated seismograms. Collapse risk from direct analysis of simulated motions is contrasted with risk estimates obtained using “conventional” approaches relying on recorded motions coupled with probabilistic seismic hazard assessments from the U.S. Geological Survey. Further, deaggregation of collapse risk is used to identify the relative contributions of causal earthquakes. Opportunities for continued research, development, and application of ground motion simulations to engineering applications are discussed.

¹Graduate Student Researcher, Blume Center for Earthquake Engineering, Stanford University, Stanford, CA 94305, USA (email: nbijelic@stanford.edu)
²Assistant Professor, Dept. of Civil, Const. and Env. Engrg., Marquette University, Milwaukee, WI 53233, USA
³Professor, Blume Center for Earthquake Engineering, Stanford University, Stanford, CA 94305, USA

Contrasting CyberShake simulations and conventional hazard analysis to assess collapse risk of tall buildings in the Los Angeles basin

N. Bijelić¹, T. Lin² and G. G. Deierlein³

ABSTRACT

Limited data on strong earthquakes and their effect on structures poses one of the main challenges of making reliable risk assessments of tall buildings. For instance, while the collapse safety of tall buildings is likely controlled by large magnitude earthquakes with long durations and low-frequency content, there are few available recorded ground motions to evaluate these issues. The influence of geologic basins on amplifying ground motion effects raises additional questions. Absent recorded motions from past large magnitude earthquakes, physics-based ground motion simulations provide an attractive alternative. This paper examines collapse performance of an archetype tall building at sites in the Los Angeles basin utilizing ground motions simulated as part of the Southern California Earthquake Center’s CyberShake project. The collapse risks of an archetype 20-story tall building are obtained using large datasets (~500,000 ground motions per site) of unscaled, site-specific simulated seismograms. Collapse risk from direct analysis of simulated motions is contrasted with risk estimates obtained using “conventional” approaches relying on recorded motions coupled with probabilistic seismic hazard assessments from the U.S. Geological Survey. Further, deaggregation of collapse risk is used to identify the relative contributions of causal earthquakes. Opportunities for continued research, development, and application of ground motion simulations to engineering applications are discussed.

Introduction

Physics-based earthquake simulations have advanced to the state of enabling detailed characterizations of extreme events allowing for novel insights into questions of engineering concern and societal importance. For instance, the Southern California Earthquake Center’s (SCEC) CyberShake project [1] performs probabilistic seismic hazard assessment (PSHA) by

¹Graduate Student Researcher, Blume Center for Earthquake Engineering, Stanford University, Stanford, CA 94305, USA (email: nbijelic@stanford.edu)
²Assistant Professor, Dept. of Civil, Const. and Env. Engrg., Marquette University, Milwaukee, WI 53233, USA
³Professor, Blume Center for Earthquake Engineering, Stanford University, Stanford, CA 94305, USA

fully relying on numerical simulation of wave propagation. By incorporation of fundamental fault rupture, site specific effects as well as effects of geologic features, physics-based simulations directly represent effects that are otherwise typically accounted for empirically by conventional ground motion prediction equations (GMPEs). Millions of site-specific seismograms are simulated in CyberShake calculations, including very extreme ground motions, which offer opportunities for novel insights in areas of earthquake engineering concern that cannot be adequately addressed using limited databases of recorded earthquakes.

The CyberShake ground motions used in this paper are classified as “hybrid-broadband” [2], which combine waveforms that are generated by physics-based earthquake rupture simulations with a high frequency stochastic component. The physics-based component of the simulations are well resolved for periods longer than one second (~ T > 1s), but due to a combination of geophysical complexity and computational limitations, the physics-based approach does not capture well the high-frequency component of ground motions. Therefore, to obtain broadband ground motions, which are required for most engineering applications, the hybrid method combines the physics-based simulation (sometimes referred to as the “deterministic” component) at longer periods with a stochastic component at higher frequencies. That is, low and high frequency seismograms are generated separately and then spliced together to form a broadband seismogram. The CyberShake ground motions have components that are spliced together at periods of about T_{splice} = 1s.

An important step toward utilizing simulated ground motions in performance-based engineering is validation to demonstrate that simulated ground motions can reliably capture features that have a significant effect on structural response (see e.g. [3, 4, 5]). For instance, it has been shown [6] that structural demands computed using simulated motions are essentially the same as recorded ground motions, when the motions are selected and scaled to common hazard targets. This present work goes a step further in validating the motions, with the broader goal of exploring the areas where simulated earthquakes can offer unique engineering insights.

To that end, this study focuses on comparative assessment of seismic performance and collapse risk disaggregation for a 20-story archetype tall building at three sites within the Los Angeles basin. One site, located in the downtown area of Los Angeles, is underlain by a soil layer about 2.1 km thick, and the second is located at a site with a much deeper layer, about 5.6 km, which is presumed to be about the thickest region of the LA basin (values used here represent depths at which shear-wave velocities equal 2.5 km/s and are obtained from SCEC Community Velocity Models). The third site is at a location where there is pronounced coupling of basin and directivity effects in the ground motions. Comparative analysis of seismic demands is performed: a) using a “conventional” approach that combines recorded ground motions with probabilistic seismic hazard targets, determined using empirically calibrated ground motion prediction equations; and b) by completely relying on physics-based CyberShake simulations to generate hazard consistent seismograms. The resulting earthquake demands on the 20-story building are compared in terms of collapse and peak story drift exceedance curves. Using the simulated motions, the collapse risk is disaggregated to investigate the sources as well as the properties of ground motions contributing to collapse. The study focuses on collapse risk since it reflects the highly nonlinear responses of structures and is a limit state of practical importance to inform decision making for building design requirements.
Case Study Buildings and Sites

Tall Building Model Description

An archetype model of 20-story reinforced concrete special moment frame is used to represent typical office buildings in California. The archetype was designed as part of a previous benchmark study [7], according to the governing provisions of the 2003 IBC, ASCE7-02 and ACI 318-02. The frame is idealized as a 2D analysis model using OpenSees [8], with a fundamental elastic period of $T_1 = 2.6s$. For additional details regarding design and modeling assumptions, see [7].

Case Study CyberShake Sites

The study compares the building performance using (1) a conventional approach, relying on United States Geological Survey (USGS) data for spectral acceleration and duration hazard targets and the Pacific Earthquake Engineering Center (PEER) Next Generation Attenuation (NGA) database [9] of recorded ground motions, and (2) a full simulation approach, where the site-specific hazard information and ground motions are obtained from the CyberShake simulations. The three L.A. basin sites chosen for this study from the CyberShake database are codenamed LADT, STNI and WNGC (latitude/longitude: 34.052 / -118.257, 33.931 / -118.178 and 34.042 / -118.065, respectively; see Fig. 1a). The LADT (Los Angeles downtown) site is of interest due to its proximity to a large inventory of tall buildings. The STNI site is situated at one of the deepest basin depths in the region, where the effects of basin structure on the resulting ground motions are very pronounced [1]. The WNGC site is interesting from the perspective that it exhibits coupling of basin and directivity effects in the ground motions [1]. For a detailed comparative discussion of seismic hazard at the considered sites, including hazard curves, conditional spectra and significant duration targets, please see [10].

![Map of CyberShake sites](image1)

Figure 1. Comparison of seismic demands: a) case study CyberShake sites locations; b) seismic demand exceedance curves of peak story drift ratios ($SDR_{max}$) obtained using conventional and CyberShake approaches.

In the conventional approach, seismic demands of a structure are estimated by performing multiple stripes analyses (MSA). Data on seismic hazard, including hazard curves and
conditional intensity measure targets, are obtained from probabilistic seismic hazard assessment (PSHA) using empirically calibrated GMPEs. Recorded ground motions are selected and scaled to match the hazard-consistent intensity targets for spectral acceleration and duration and then used as input for nonlinear response history analyses to obtain building response. For these conventional analyses, we utilized PSHA results from USGS and recorded motions from PEER NGA database.

In contrast, the CyberShake simulated earthquake data enable more direct assessment of earthquake demands. Nonlinear response history analyses are performed using all the simulated ground motions at the three considered sites (~500,000 seismograms per site), where each simulated ground motion is associated with a frequency of occurrence from the UCERF2 earthquake rupture forecast model. In this way, the seismic demands are directly obtained, sidestepping the need for PSHA intensity measures and selection and scaling of recorded motions.

Results of the conventional and CyberShake-based direct analyses are compared in Fig. 1b, in terms of exceedance curves of peak story drift ratios ($SDR_{max}$). As seen from the figure, the two analyses yield similar results for the LADT site, with the differences being the largest for mildly nonlinear drifts. The source of these differences can be traced primarily to the differences in the (implied) seismic hazard curves [10]. The results for WNGC site are similar to LADT, with somewhat larger differences in drift exceedances in mildly nonlinear range. In contrast, for the STNI site, the two analyses yield drastically different results, where the mean annual frequency of collapse for the CyberShake data is about ten times larger than the result based on conventional analysis. This confirms the observations as obtained from MSA as reported in [10]. The STNI results provide a compelling case where the simulated CyberShake ground motions provide unique insights for reliably estimating building seismic risk.

**Disaggregation of Collapse Risk**

Apart from more explicit representation of unique geological (basin) features, the direct analyses using Cybershake motions allow for additional interpretation of the results. For instance, the collapse risk can be disaggregated and linked to causative ground motions and source properties. Here, we focus on contrasting disaggregation of collapse risk for a 20-story building to the and disaggregation of seismic hazard at the building site. The $Sa$ seismic hazards are considered for a 2% in 50-year exceedance rate for periods of 3 and 5 seconds, which relate to the first-mode period and an elongated first-mode period. As shown in Fig. 2a-c, at the LADT site, the collapse risk disaggregation is similar to that of the $Sa(T=3s)$ hazard. Conversely, at the STNI site (Fig. 2d-f), the collapse risk is characterized by a higher contribution of more distant larger magnitude earthquakes, which is more like the disaggregation at $Sa(T=5s)$. Comparisons of disaggregation at the WNGC site (Fig. 2g-j) are much like the observations at the LADT site.

Contribution of different ruptures to collapse risk and seismic hazard for the LADT and STNI sites are further compared in Fig. 3. For LADT, the Puente Hills ruptures dominate the collapse risk (contributing around 50%), followed by ruptures on Newport Inglewood and Raymond faults. There are also significant contributions from Elsinore and Palos Verdes faults, with very low contributions (around 1%) from ruptures on the San Andreas (for relative location of the
faults, see Fig. 4). At the STNI site, the largest contributions come from Elsinore fault (on the order of 25%), followed by Puente Hills, Palos Verdes and Newport Inglewood faults in relatively similar proportions. There is also a higher contribution (~12%) of the San Andreas fault to the collapse risk. Distribution of sources contributing to 2% in 50 years Sa(T=3s) hazard are generally similar to sources contributing to collapse risk, although the Puente Hills fault hazard contribution (~25%) is about half that of the collapse risk contribution at the LADT site. While not shown in the figure, the contribution of sources at the WNGC site is similar to LADT.

![Graphs showing collapse risk and seismic hazard disaggregation at case study sites]

Figure 2. Collapse risk and seismic hazard disaggregation at case study sites: a-c) LADT site; d-f) STNI site; g-j) WNGC site.
Figure 3. Contribution of different sources to collapse risk and 2% in 50 years hazard of $\text{Sa}(T=3\text{s})$: a) LADT; b) STNI.

Figure 4. Subset of faults contributing to seismic hazard and risk in the Los Angeles basin.

Ground motion characteristics (spectral shape and durations) of causative motions from various M-R bins contributing to collapse risk at the STNI site are shown in Fig. 5. Notably, the ground motions from different bins exhibit distinctly different spectral shapes. For instance, the ground motions from bin A (closer distance, smaller magnitude) exhibit peaked spectra with lower long period energy and shorter durations. Conversely, ground motions from bins B and C (larger
magnitude, with shorter and longer distances, respectively) have flatter spectra, with significant longer period energy and longer durations. Hence, the figure demonstrates that the effects of duration are captured by distinct spectral shapes of the unscaled simulated CyberShake seismograms. Finally, the strong discriminative power of SaAverage and significant duration for predicting collapse is observed from the scatter plots in Fig. 5. Similar observations were observed by the authors at the other two sites.

Figure 5. Spectral shapes and durations of STNI ground motions from different M-R bins in collapse risk disaggregation. Bins A, B, and C are as reported in Fig. 2. In the scatter plots (bottom row), blue circles indicate non-collapsing motions while the red ones indicate collapsing motions; indicated with green are the motions from a particular M-R bin.

Conclusion

This paper contrasts the use of CyberShake simulations and conventional hazard analysis to perform analysis and disaggregation of collapse risk of an archetype tall building at three sites in the Los Angeles basin. The first site (LADT) is located in L.A. downtown, where most of the tall buildings are situated; the second site (STNI) is at one of the deepest basin sites in the region, and the third site (WNGC) is where there is strong coupling of basin and directivity effects in the ground motions. The seismic demands obtained using the conventional and CyberShake-based approaches were similar at the LADT and WNGC sites but are drastically different at the deep basin site. In particular, the estimate of mean annual frequency of collapse based on simulations at the deep-basin site was roughly 10 times larger compared to the conventional estimate. Disaggregation of collapse risks allows examination of the dominating earthquake sources (contributing faults, M-R events) as well as the properties of contributing ground motions.

The study described in this paper is part of a larger effort by the engineering and earth science research community to validate simulations and to explore areas where ground motion
simulations can provide unique insight to earthquake engineering challenges that cannot be fully addressed using limited data on recorded strong earthquakes. Ground motion simulation is still a rapidly evolving field, so the analyses presented here are by no means complete or comprehensive. Rather, they are a step towards exploring the future promise of simulations and helping to identify and direct efforts to improve ground motions simulations and make them useful for engineering applications.

Acknowledgements

This research is supported by the Fulbright S&T Program, the John A. Blume Earthquake Engineering Center, the Shah Family Fellowship and the Southern California Earthquake Center (SCEC projects #13161, 14228, 15113, 16139). The authors gratefully acknowledge researchers associated with SCEC for developing and advancing ground motion simulations, including (1) Robert Graves, Phil Maechling, Scott Callaghan and Kevin Milner for their support and help with CyberShake simulations, and (2) the PEER Center for providing the NGA database. Analyses presented herein were performed using the Sherlock computing cluster at Stanford University.

References