Application of Scenario Physics-Based Ground Motion Simulations to Improve Seismic Risk Assessment for Regional Building Inventories

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SUMMARY

Our 2012 research is best described in two phases. In Phase 1 we examine spatial correlations between building response parameters and ground motion intensity. A critical observation is that spatial correlations between engineering demand parameters (*i.e. EDP*s, particularly interstory drift) and spectral accelerations at a building's fundamental period ($Sa(T_1)$) are very similar, when evaluated in natural log space. Based on this observation, we propose that existing models for generating spatially distributed ground motion intensities (*i.e.* $Sa(T_1)$) be complemented with a method that uses them to produce probabilistically robust spatially distributed building responses (*i.e. EDP*s). The proposed method preserves the spatial correlations between intensity that are observed in $Ln[Sa(T_1)]$ and $Ln[EDP]$. Considering these spatial correlations has been shown to reduce bias in predicting regional seismic losses (Park *et al.* 2007). Since *EDP*s are better predictors of damage/loss than $Sa(T_1)$, such a process is expected to be of significant worth for estimating cumulative losses to building stocks that are distributed throughout a region. This method for simulating EDPs from $Sa(T_1)$s is intended to be used in a Monte Carlo framework for regional loss estimation.

In Phase 2, a case study is conducted to evaluate seismic-induced losses to the downtown Los Angeles RC frame building stock, due to a magnitude 7.8 south-to-north rupture along the San Andreas Fault, by three different methods. It is observed that robust techniques for simulating ground shaking intensity (*e.g.* those that consider spatial correlations of the intensity) are vital for simulating large rare losses. Even so, these methods may not be sufficient. In particular, a method for simulating spatially correlated EDPs, such as the one developed in Phase 1, can be employed to fully capture the effects of large rare losses when performing probabilistic regional seismic loss analysis.

1 INTRODUCTION

The development of performance-based earthquake engineering methods has been primarily concerned with the assessment of earthquake-induced losses and collapse risk in individual buildings. While beneficial when examining design or retrofit alternatives for specific structures, this unit of analysis is problematic for making regional or policy decisions about seismic design and mitigation, because the metrics of building performance obtained through such methods are decoupled from the unit of decision, *i.e.* communities or regions. Tools for predicting seismic losses in a geographically-distributed building inventory are in need of further refinement, and can benefit from recent advancements in performance-based analysis of infrastructure systems.

1.1 *Probabilistic Methods for Regional Loss Assessment*

In this study, the term "regional loss" refers to the total loss to all of the individual buildings belonging to a building stock (or portfolio of buildings) that are located in a specified area or region. A common metric for presenting risk-based regional loss estimations is via mean rates of exceedance (MRE). MREs represent the temporal rates (*i.e.,* frequencies) at which earthquake-induced losses are expected to exceed a set of threshold (dollar) values. The distribution of possible losses for a region or building portfolio may be estimated by performing the following steps, which accounts for the many sources of uncertainty in regional loss estimates:

1. Identify all relevant faults and the distributions of potential earthquake magnitudes and rupture locations.
2. Use a Monte Carlo simulation approach to generate a suite of realizations of possible earthquake scenarios that is consistent with the distributions of potential magnitudes and earthquake locations.
3. For a given scenario, use a ground motion prediction equation (GMPE), *e.g.* Boore and Atkinson (2008), to compute the expected ground motion intensity measure (IM) at each site. The GMPE also quantifies the dispersion (logarithmic standard deviation) in this prediction.
4. Generate realizations of IM values at each site, based on the expected value and standard deviation of IM defined in *step 3*. This step creates a map that represents one possible realization of ground motion intensities in the region for the scenario of interest.
5. Compute the loss for each building, based on IM and a predefined damage function (DF). A DF is a relationship between an input parameter, *e.g.* IM, or a measure of structural response, known as an engineering demand parameter (EDP), and the expected (mean) loss for a building.
6. Sum the losses from each building to get the total expected loss to the building portfolio.
7. Repeat *steps 3-6* for multiple Monte Carlo realizations of each potential scenario.

Finally, results for multiple realizations of the same scenario and multiple scenarios, taking into consideration the recurrence intervals of each of the rupture scenarios, are combined to compute the MRE for various loss thresholds.

In the last decade, several contributions have been made to the probabilistic regional loss estimation procedure that is described above (*e.g.* Bazzurro and Luco 2005, Lee and Kiremidjian 2007, Park *et al.* 2007, Goda and Hong 2008a, Jayaram and Baker 2010, Vaziri *et al.* 2012). A number of these studies demonstrate that consideration of spatial correlations in ground shaking intensity has a large influence on the probabilistic distribution of losses predicted for a regionally distributed building stock. In particular, large, rare losses are underestimated when spatial correlation is ignored in generating maps of ground shaking intensity (*e.g.* in *step 4* in the probabilistic regional loss estimation method described above). This observation can be intuitively understood by the notion that large losses occur when ground shaking intensity is above average all throughout a region, which occurs as a result of site-to-site correlations of ground shaking intensity.

1.2 *Advancements to Regional Loss Assessment through Consideration of Building Response Correlations*

Much progress has been made in quantifying the impacts of spatial correlations in *ground shaking intensity* on probabilistic regional loss analysis. This study, for the first time, examines the impact of spatial correlations in *building response* on regional seismic loss. The work completed in 2012 was conducted in two phases. Phase 1 investigates spatial correlations of building responses in earthquake scenarios and proposes a method for incorporating its findings into the Monte Carlo loss estimation procedure described in Section 1.1. Phase 2 is an ongoing case study, which illustrates the importance of considering robust simulations of building responses (*i.e.* those that have accurate spatial correlations) for regional seismic loss assessment.

2 PHASE 1: INCORPORATION OF SPATIAL CORRELATIONS BETWEEN BUILDING RESPONSE PARAMETERS IN REGIONAL SEISMIC LOSS ANALYSIS

2.1 *Data*

The first part of the study quantifies correlations in building response by simulating nonlinear building response when subjected to ground motion time histories from three historical and two hypothetical (simulated) earthquake scenarios (Table 1).

Table 1. Earthquake events used in nonlinear time-history analyses.

Earthquake	Magnitude (M_w)	No. of sites for which time histories are used	Max. PGA (g)	Min. PGA (g)	Site spacing (km)	Max. inter-site distance (km)
Recorded						
Loma Prieta	6.9	82	1.16	0.005	Irregular	260
Northridge	6.7	245	1.78	0.028	Irregular	275
Chi Chi	7.6	420	1.16	0.005	Irregular	378
Simulated						
Puente Hills	7.2	875	1.45	0.097	3	124
ShakeOut	7.8	734	1.31	0.009	10	460

The historical events considered are the 1989 Loma Prieta (California), 1994 Northridge (California), and 1999 Chi Chi (Taiwan) earthquakes. For each of these events, a relatively large number of recordings are available, which were downloaded from the PEER ground motion database. The simulated events represent two plausible Southern California earthquake scenarios: a Puente Hills fault rupture, and the “ShakeOut” South-to-North rupture of the San Andreas fault. For these scenarios, Graves *et al.* (2005; 2008) predicted ground shaking time histories at a large number of sites through broadband physics-based simulations of fault rupture and seismic wave propagation.

Predictions of nonlinear dynamic response are obtained from six building models, created by Haselton *et al.* (2011) and Liel *et al.* (2011). The building models range in height from two to eight stories and include both modern ductile and older nonductile reinforced concrete (*RC*) moment frame buildings, in order to capture behavior indicative of a wide range of building types. Each of these building frame models was subjected to the ground motion time histories recorded or simulated at each site for each of the earthquake scenarios (Rowe, 2011). For each nonlinear time history analysis, engineering demand parameters (*EDP*s) such as interstory drift ratios (*IDR*), peak floor accelerations (*PFA*), beam plastic hinge rotations (*BPHR*), and column plastic hinge rotations (*CPHR*) are recorded. These *EDP*s are proxies for building damage (Porter *et al.* 2007).

2.2 *Findings*

The spatial correlations of the building responses (EDPs), as well as spectral acceleration at the buildings' fundamental periods (Sa(T_1)), are computed for each of the earthquake events. Correlations between responses of the same building, but at different sites, are referred to as "self-correlations". Self-correlations are cross-correlations of a variable with itself, *i.e.* autocorrelations (Bennett 1979). We also compute correlations between responses of different (non-identical) buildings as a function of site separation distance, which are termed "cross-correlations". It is found that self-correlations and cross-correlations of EDPs are extremely similar to self-correlations and cross-correlations of Sa(T_1), when evaluated in natural log space. Figure 1 is an example of the spatial self-correlations for Building 1 for the Northridge Earthquake. Similar results were obtained for all of the other buildings as well as for a 1-story short period (0.3 sec) wood-frame shear wall structure. Cross-correlations are larger for buildings that are more similar (as quantified by first- mode period and ductility).

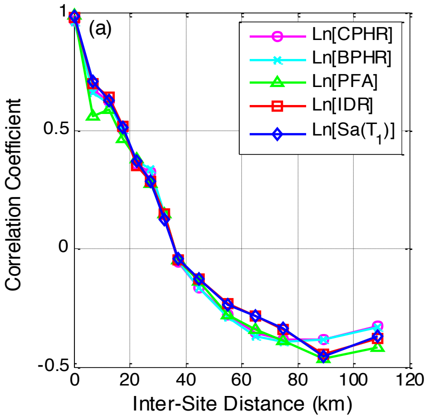

Figure 1. Spatial correlations between IM (*Ln[Sa(T_1)]*) and EDPs (*Ln[IDR], Ln[PFA], Ln[BPHR]* and *Ln[CPHR])* for an identical building (Building 1) located at different sites affected by the Northridge earthquake.

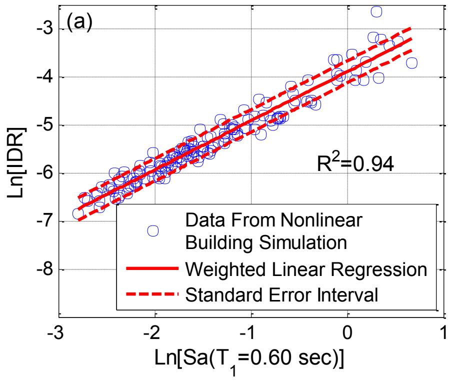

Figure 2. Weighted least squares linear regression of *Ln[IDR]* with *Ln[Sa(T_1)],* for Building 1, Northridge earthquake.

2.3 *Application to Regional Seismic Loss Assessment*

The similarities in spatial correlation structures of Ln[EDP] and Ln[Sa(T1)] stems from an underlying linear relationship between the ground motion intensity and building response, which is illustrated with simulated building response data for the Northridge earthquake in Figure 2. The parameters defining the linear relationship between Ln[Sa(T1)] and Ln[EDP] vary depending on the properties of the earthquake (and ground shaking characteristics) and the properties of building. However, we found that the slope and intercept parameters defining the linear relationship, for a given building, follow a joint normal distribution that can be determined a priori via incremental dynamic analysis (IDA) of the building model. By taking a random sample from this distribution of building specific slope and intercept values, it is possible to transform a map of Sa(T1) values to a map of EDP values. This linear transformation preserves the correlation structure expected in building response EDPs. This process for generating EDPs can be directly incorporated into the Monte Carlo regional loss estimation procedure that is explained in the introduction. Rather than computing losses directly from IMs (step 5), one can generate a probabilistically consistent map of EDP values using our method, and then compute the building losses in step 5 from DFs that are based on EDP rather than on IM. The advantage of this approach is that EDPs are better predictors of building loss than IM, because damage is more strongly tied to building response than to ground shaking intensity, and the correlations in building EDPs are explicitly considered.

3 PHASE 2: A SCENARIO CASE STUDY TO EVALUATE METHODS OF SEISMIC LOSS ASSESSMENT FOR COMMUNITIES OF BUILDINGS

3.1 *Comparison of Methods*

In this phase, regional losses are computed for concrete moment frames in the downtown Los Angeles area, due to the ShakeOut earthquake event, by three different methods. The purpose of selecting these different methods is to interrogate the impacts of neglecting or including spatial correlations in IM and EDP on regional loss estimates. The three methods are defined as follows. First, the "Benchmark" method evaluates the regional loss based on EDPs that are computed from nonlinear dynamic time-history analysis with the ShakeOut ground motion time-histories and building-specific loss assessment. The "Benchmark" method is considered the most robust estimation that we can achieve, providing values by which the other values can be compared. The second method, the so-called "Pre-2005" method, estimates regional losses based $Sa(T_1)$s that are predicted from a GMPE. Losses are predicted from building specific damage functions relating site IMs to dollar losses. As the name implies, the "Pre-2005" analysis is intended to represent the state-of-the-art in regional loss estimations before the year 2005 (*i.e.* no consideration of spatial correlations of IMs in step 4 of the loss estimation procedure). Finally, the "Post-2005" method evaluates the regional loss based on $Sa(T_1)$ values that are recorded at each site for from the ShakeOut simulation. The "Post-2005" method considers spatial correlations of IMs. Losses are again predicted from IM-based damage functions.

3.2 Findings

The results in Table 2 show that each regional loss estimation method produces different results for test building stock of 900+ reinforced concrete buildings affected by the ShakeOut event. As expected, the "Pre-2005" method significantly underestimates the regional loss for the case-study building stock (relative to the "Benchmark" results). This underestimation occurs because the "Pre-2005" neglect spatial correlations in ground motion intensity. However, the ground motion intensities from the ShakeOut scenario, which are used in the other methods, are above the expected value at virtually every site, as is characteristic of events that cause large losses. Although much closer to the "Benchmark" than the "Pre-2005" method, the "Post-2005" method still misestimates the regional loss by -37%. This means that, while robust spatially correlated estimations of ground shaking intensity maps are necessary for probabilistic regional loss estimation, they are not sufficient. The results suggest that regional loss estimation procedures may benefit from a robust method for generating correlated maps of EDPs, such as the method we developed in Phase 1 of our 2012 work, because regional loss cannot be fully explained by only $Sa(T_1)$ intensity maps.

4 ONGOING RESEARCH

The case study regional seismic loss analysis (Phase 2 of the 2012 work) is an ongoing project. Future research plans include conducting additional regional loss assessments for scenario case study test regions of differing sizes and building densities. We will also examine the implications of additional loss estimation methods and explore the sensitivity of the loss estimates to the characteristics of the building inventory. The results of these additional case studies will provide valuable information for Phase 3 of our regional loss assessment research. In Phase 3, probabilistic regional loss assessments will be performed by Monte Carlo simulation procedures that implement the tools we have developed for generating (stochastically) maps of EDP accounting for a suite of possible future earthquake scenarios. The primary goals of the Phase 3 research efforts are to (1) test the simulation method we have developed (*i.e.* the method developed in Phase 1 to generate EDP maps from IM maps), (2) investigate the impacts of importance sampling, and make recommendations for using importance sampling to "streamline" the Monte Carlo regional loss estimation procedure, and (3) develop simplified techniques to account for building by building correlations in regional loss estimation.

Table 2. Losses for the case-study building stock, given the Shakeout earthquake scenario (in 2009 $).

Analysis	Model building (results summed for all buildings in the test region)						Entire stock
	1	2	3	4	5	6	
"Benchmark"							
$ (x 10^6)	74	93	1,668	534	2,410	1,608	**6,378**
Pre-2005							
$ (x 10^6)	108	136	254	266	511	323	**1,605**
Post-2005							
$ (x 10^6)	106	104	526	168	1,850	1,258	**4,005**

5 OUTREACH

In 2012 and 2013 we have shared this ongoing research with other students, researchers, and professionals. Ph.D. Candidate D. Jared DeBock attended the 2012 SCEC conference in Palm Springs, CA, where he presented a poster of this research. Healso presented an additional poster about this research at the 2013 EERI annual meeting in Seattle and at a graduate student poster session at the University of Colorado.

Dr. Abbie B. Liel and D. Jared DeBock will also present the findings of this research at the 2013 ICOSSAR conference in New York, NY, via a conference paper and a presentation.

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PUBLICATIONS SUPPORTED BY SCEC FUNDS

Publications based on SCEC-funded work completed in 2012

One journal paper and one conference paper have been written, based on the research work conducted in 2012, and will be submitted soon.

DeBock, D.J., J.W. Garrison, K.Y. Kim, A.B. Liel (2013). "Incorporation of spatial correlations between building response parameters in regional seismic loss analysis," *Bull. Seismol. Soc. Am.* Near submission.

DeBock, D.J., K.Y. Kim, A.B. Liel (2013). "A Scenario Case Study to Evaluate Methods of Seismic Loss Assessment for Communities of Buildings." *International Conference on Structural Safety and Reliability (ICOSSAR).* New York, NY. Submission deadline is April 1, 2013; Abstract is accepted.

Posters presented in 2012

DeBock, D.J., J.W. Garrison, A.B. Liel (2012). Spatial Correlations in Building Response Using Simulated and Recorded Earthquake Scenarios. Southern California Earthquake Center Annual Meeting.

DeBock, D.J., J.W. Garrison, K.Y. Kim, A.B. Liel (2013). Incorporation of Spatial Correlations between Building Reponses Parameters in Regional Seismic Loss Analysis. EERI Annual Meeting.

Publications based on SCEC-funded work completed prior to 2012

Lynch, Kathryn P., Kristen L. Rowe, Abbie B. Liel, Seismic Performance of Reinforced Concrete Frame Buildings in Southern California, Earthquake Spectra, 27(2), pp. 399-417, 2011.

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