UC Irvine

UC Irvine Previously Published Works

Title

An Applied Method for General Regional Seismic Loss Assessment—With A Case Study in Los Angeles County

Permalink

<https://escholarship.org/uc/item/2dp259t5>

Journal

Journal of Earthquake Engineering, 22(9)

ISSN

1363-2469

Authors

Esmaili, O
Grant Ludwig, L
Zareian, F

Publication Date

2018-10-21

DOI

10.1080/13632469.2017.1284699

Peer reviewed

An Applied Method for General Regional Seismic Loss Assessment—With A Case Study in Los Angeles County

Omid Esmaili, Lisa Grant Ludwig & Farzin Zareian

To cite this article: Omid Esmaili, Lisa Grant Ludwig & Farzin Zareian (2018) An Applied Method for General Regional Seismic Loss Assessment—With A Case Study in Los Angeles County, Journal of Earthquake Engineering, 22:9, 1569-1589, DOI: [10.1080/13632469.2017.1284699](https://doi.org/10.1080/13632469.2017.1284699)

To link to this article: <https://doi.org/10.1080/13632469.2017.1284699>

Published online: 27 Apr 2017.

Submit your article to this journal [↗](#)

Article views: 230

View Crossmark data [↗](#)

An Applied Method for General Regional Seismic Loss Assessment—With A Case Study in Los Angeles County

Omid Esmaili^a, Lisa Grant Ludwig ^b, and Farzin Zareian^c

^aDepartment of Civil and Environmental Engineering, University of California – Irvine, Irvine, California, USA;

^bProgram in Public Health, University of California – Irvine, Irvine, California, USA; ^cDepartment of Civil and Environmental Engineering, University of California – Irvine, Irvine, California, USA

ABSTRACT

We describe the formulation and application of an integrated general regional seismic loss assessment (RSLA) method for buildings in seismic regions. An efficient method for RSLA is valuable for engineers involved in city planning, risk management, and insurance dealings. In contrast to previously reported methods, the framework presented herein is hazard-based and utilizes a regional rapid seismic hazard deaggregation tool that allows regional assessment to be conducted more efficiently. The proposed technique is implemented as an example to assess general regional seismic loss in Los Angeles County for a ground motion hazard with 10% probability of exceedance in 50 years.

ARTICLE HISTORY

Received 7 February 2016

Accepted 17 January 2017

KEYWORDS

Regional Seismic Loss Assessment; Los Angeles County; Performance-Based Seismic Assessment; Vulnerability; Seismic Risk

1. Introduction

Damages from major earthquakes in the past few decades highlight the vulnerability of existing buildings and exemplify the importance of conducting urban-scale seismic vulnerability assessments in high seismic hazard regions [Tesfamariam and Liu, 2010]. Seismic loss assessment of individual buildings has advanced in recent years from being solely empirical (e.g., Barbat *et al.* (1996); Whitman *et al.* (1997); FEMA (1999, 2001, 2003)) to a combination of empirical and mechanistic (e.g., FEMA (2006, 2012); Cornell and Krawinkler (2000); Krawinkler (2002); Miranda and Aslani (2003)). In this context, The Pacific Earthquake Engineering Research (PEER) Center has developed a framework for Performance-based Seismic Assessment (PBSA) that relies on integrating models and knowledge from seismology, structural engineering, and social sciences. This framework is used to obtain probabilistic predictions of seismic hazard, structural response, damage, economic losses, and casualties (e.g., Deierlein (2004); Krawinkler and Miranda (2004)). More recent research in this field focuses on improving data for PBSA and/or simplifying the methodology involved in assessing individual buildings (e.g., Ramirez and Miranda (2009)). While seismic loss assessment of individual buildings is useful for examining design or retrofit alternatives for specific structures, this information on its own is insufficient for use in policy making decisions regarding seismic design and mitigation. This is because the metrics of building performance obtained through seismic loss

CONTACT Omid Esmaili oesmaili@uci.edu Department of Civil and Environmental Engineering, University of California – Irvine, Irvine, California 92697-2715, USA.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ueqe.

© 2018 Taylor & Francis Group, LLC

assessment methods are decoupled from the units of decision, i.e. communities or regions [DeBock *et al.*, 2013]. Spatial correlations in ground motion intensity are important for quantifying earthquake induced damage and losses experienced by a group of spatially distributed buildings [DeBock *et al.*, 2014]. Therefore, a number of research studies have been conducted to develop models that quantify regional correlations in ground motion intensities (e.g., Wesson and Perkins (2001); Wang and Takada (2005); Goda and Hong (2008b); Goda and Atkinson (2009), Jayaram and Baker (2009); Sokolov *et al.* (2010), Esposito and Iervolino (2011); Loth and Baker (2013); Du and Wang (2013)). Other studies [Bazzurro and Luco, 2005; Lee and Kiremidjian, 2007; Park *et al.*, 2007; Goda and Hong, 2008a; DeBock *et al.*, 2014] have shown that spatial correlations in ground shaking intensity have largely influenced the probabilistic distribution of losses predicted for a regionally distributed building stock [DeBock *et al.*, 2013]. Some of these studies [Ebel and Kafka, 1999; Bazzurro and Luco, 2005; Crowley and Bommer, 2006; Werner *et al.*, 2006] implemented the Monte Carlo Simulation (MCS) as an alternative method for general regional seismic loss assessment (RSLA), which retained the ability to identify the contributions of specific earthquake events to the regional risk [Vaziri *et al.*, 2012]. However, the MCS method can be computationally intensive, which could be impractical if the analysis must be repeated many times. To address the computational difficulty of MCS, we implement methods, first developed by Chang *et al.* [2000] and Shiraki *et al.* [2007], that fall into the hazard-consistent probabilistic scenario approach. These methods identify a relatively small subset of all possible earthquakes. The annual occurrence probability of each earthquake is adjusted so that each subset of events represents all events with a similar geographic distribution and ground motion intensity. The subset of events, along with the adjusted hazard-consistent occurrence probabilities, represents the total regional hazard. Losses are then estimated in the same manner as in MCS. Besides the methods discussed above, a comprehensive comparison has been made by Daniell [2009, 2011] between different earthquake loss estimation tools from different aspects such as their applicability regions, exposure resolution (district, city, regional, and country), hazard (deterministic predicted, deterministic observed, probabilistic), and vulnerability type (analytical, empirical, and socioeconomic). A comparison of five selected European earthquake loss estimation tools such as KOERILOSS-ELER, SELENA, ESCENARIS, SIGE-DPC, and DBELA have been also provided by Strasser *et al.* [2008]. Similar to HAZUS-MH [FEMA, 2003], SELENA [Molina and Lindholm, 2005], NHEMATIS [Couture *et al.*, 2002], and LNECloss [Sousa *et al.*, 2004] can be mentioned among many others as earthquake loss assessment tools integrated on a Geographic Information System (GIS).

The RSLA approach proposed in this paper is a hazard-consistent methodology that is also taking advantage of GIS. This approach offers several advantages, including conceptual straightforwardness while implementing MCS. The RSLA approach can efficiently show potential vulnerable zones with a normalized general expected loss value larger than a threshold (e.g., $15\% < \theta_l^R$) at the specific hazard level (e.g., 10% chance of exceedance in 50 years, or design basis earthquake (DBE)). In other words, the proposed method returns an upper bound of normalized general regional expected loss value, which is a valuable estimate in light of all uncertainties and computational overhead involved in generating RSLA using realistic scenarios. We demonstrate the proposed RSLA technique by assessing the general regional seismic loss in Los Angeles County for a ground motion hazard

with 10% probability of exceedance in 50 years. For simplification purposes, the area is assumed to be predominantly occupied by four-story reinforced concrete moment frame (RCMF) buildings. Twenty-seven combinations of building models are used to have a better representation of all the four-story RCMF buildings in Los Angeles County. In reality, the actual building stock should be considered with all possible diversities between buildings, and each should be characterized by its own unique numerical model. Such an approach, however, is highly computationally intensive and infeasible given the current state of available information.

2. Theory

2.1. Site-specific seismic loss assessment

This section provides an overview of site-specific loss assessment for specific building classes. Class i of buildings, C_i (which denotes the i th group of buildings with similar structural and nonstructural specifications), is assumed. Each building class corresponds to a specific site with a given vector of ground motion intensity, $\mathbf{IM}$, for a specific earthquake hazard level. For each story level f of a building, let θ_l^{f,C_i} denote the building's performance measure (e.g., monetary loss, θ_l). A proper notation is to use $(\theta_l^{f,C_i}|\mathbf{IM})$, but in order to make the equations and derivations less cumbersome, the change in notation is adopted interchangeably. The performance measure can be calculated from the PEER-PBSA framing equation (Eq. (1)). It deals with loss at the story level as opposed to the traditional application of this general equation at the building level.

$$G_{(\theta_l^{f,C_i}|\mathbf{IM})}(z|x) = \int_u \int_v \int G_{(\theta_l^{f,C_i}|\mathbf{L})}(z|u) f_{(\mathbf{L}|\mathbf{DS})}(u|v) f_{(\mathbf{DS}|\mathbf{EDP}^f)}(v|y) f_{(\mathbf{EDP}^f|\mathbf{IM})}(y|x) . du dv dy \quad (1)$$

In Eq. (1), $\mathbf{EDP}|\mathbf{IM}$ is a vector of engineering demand parameters that characterizes the response of the structure for a given vector of ground motion intensity measures, $\mathbf{IM} = \mathbf{im}$; $\mathbf{DS}|\mathbf{EDP}$ is a vector of damage states for each component, given seismic demand $\mathbf{EDP} = \mathbf{edp}$; $\mathbf{L}|\mathbf{DS}$ is a vector of losses incurred in each component due to damage states, $\mathbf{DS} = \mathbf{ds}$; and θ_l^f is the total story loss. Also, $G_{(X|Y)}(x|y) = P(X \geq x|Y = y)$ is the cumulative distribution function (CDF) of X given $Y = y$; $f_{(X|Y)}(x|y)$ is the probability density of X given $Y = y$; and $\theta_l^f(Z)$ is the annual frequency of Z exceeding z for a given hazard curve. It should be noted that Eq. (1) assumes conditional independence (e.g., damage state, $\mathbf{DS}$, is only a function of $\mathbf{EDP}$, and not of the $\mathbf{IM}$ causing $\mathbf{EDP}$), and therefore, can be de-coupled and solved in separate stages. Markovian dependence is assumed for all conditional distributions in Eq. (1). Without losing generality, the study presented herein is conducted for a scalar representation of ground motion intensity measure; hence, a scalar notation for $\mathbf{IM}$ is used hereafter.

$$(\mathbf{EDP}^f|\mathbf{IM}) = \left[IDR_{max.Dir-1}^f, PFA_{Dir-1}^f, IDR_{max.Dir-2}^f, PFA_{Dir-2}^f \right] \quad (2)$$

Eq. (2) shows a typical $\mathbf{EDP}^f|IM$ vector that includes values of maximum interstory drift ratio, IDR_{max}^f , and peak floor acceleration, PFA^f , at story level f for horizontal ground acceleration components (i.e., denoted with Dir -1, and -2 indices), at a given level of ground motion IM . The $\mathbf{EDP}^f|IM$ vector shown in Eq. (2) is “typical” because current loss assessment tools use drift and acceleration response of stories as EDPs for loss estimation. To generalize the loss estimation process, we focus on a normalized value of loss. We implement normalized story-based EDP - DV functions that relate groups of $EDPs$ directly to corresponding normalized economic losses as the decision variables (DVs). These functions can be formulated independently by first computing the third stage of Eq. (1), which allows for data reduction and less computational effort [Ramirez and Miranda, 2009].

Summing the individual loss components for the entire story of a building requires inventorying the number of building components and the value of each component type. Generic EDP - DV functions can be formulated if components of the same type are grouped together and assumed to experience the same level of damage. Addressing how to derive generic normalized story-based EDP - DV functions and cost distributions is beyond the scope of this research. Readers are referred to a wealth of literature on this subject, some of which is summarized by Ramirez and Miranda [2009]. Incorporating this change will transform Eq. (1) into Eq. (3) where $E^{norm}[\theta_l^{f,C_i}|IM]$ represents the expected normalized loss of story level f of a building given the level of ground motion intensity measure, IM .

$$E^{norm}[\theta_l^{f,C_i}|IM] = \int_y E^{norm}[\theta_l^{f,C_i}|x] f_{(\mathbf{EDP}^f|IM)}(y|x) \cdot dy \quad (3)$$

Inclusion of probability of total failure, i.e. collapse, in loss estimation requires partitioning the loss space into two mutually exclusive and collectively exhaustive subspaces: (a) collapse and (b) noncollapse. With this assumption, the expected normalized loss value in the story level f can be estimated using Eq. (4), where $E^{norm}[\theta_l^{f,C_i}|NC.IM]$ is the expected loss value in story level f of the building due to noncollapse damages normalized by the replacement cost of story level f , $P(NC|IM)$ is the probability of noncollapse given IM , $E^{norm}[\theta_l^{f,C_i}|C, IM]$ is the cost of collapse of the story normalized by the replacement cost of story level f , and $P(C|IM)$ is probability of collapse given IM , where $P(NC|IM) = 1 - P(C|IM)$. In order to fully incorporate RSLA into regional loss estimation methods, partitioning the total value of loss into drift-sensitive components and acceleration-sensitive components is considered [Krawinkler *et al.*, 2006].

$$E^{norm}[\theta_l^{f,C_i}|IM] = E^{norm}[\theta_l^{f,C_i}|NC.IM]P(NC|IM) + E^{norm}[\theta_l^{f,C_i}|C.IM]P(C|IM) \quad (4)$$

Therefore, the ratio of drift-sensitive components' loss to the total value of loss at the story level f is introduced as γ ; i.e., $\left(\theta_l^{f,C_i}\right)_{IDR} / \left(\theta_l^{f,C_i}\right)$; also $\left(\theta_l^{f,C_i}\right)_{PFA}$ represents acceleration-sensitive components' loss at story level f . From Eq. (2), $\mathbf{EDP}^f$ vectors consist of IDR_{max}^f and PFA^f for horizontal ground acceleration components. Consequently, to use generic normalized story-based EDP - DV functions, losses are also categorized as either drift-sensitive or acceleration-sensitive. In Eqs. (5)–(7), $E^{norm}[\theta_l^{T,C_i}|NC, IM]$ is the building's expected loss value due to damages (i.e., noncollapse) normalized by the building's

replacement cost, and N is the number of stories in the building. The total loss of the building is estimated using Eq. (8).

$$E^{norm}[\theta_l^{f,C_i}|NC, IM] = \gamma.E^{norm}[\theta_l^{f,C_i}|_{IDR}|NC, IM] + (1 - \gamma).E^{norm}[\theta_l^{f,C_i}|_{PFA}|NC, IM] \quad (5)$$

$$E^{norm}[\theta_l^{T,C_i}|NC, IM] = \left(\frac{1}{N}\right) \sum_{f=1}^N E^{norm}[\theta_l^{f,C_i}|NC, IM] \quad (6)$$

$$\begin{aligned} E^{norm}[\theta_l^{T,C_i}|NC, IM] \\ = \left(\frac{1}{N}\right) \sum_{j=1}^N \left\{ \gamma.E^{norm}\left[\left(\theta_l^{f,C_i}\right)_{IDR}|NC, IM\right] + (1 - \gamma).E^{norm}\left[\left(\theta_l^{f,C_i}\right)_{PFA}|NC, IM\right] \right\} \end{aligned} \quad (7)$$

$$E^{norm}[\theta_l^{T,C_i}|IM] = E^{norm}[\theta_l^{T,C_i}|NC, IM]P(NC|IM) + E^{norm}[\theta_l^{T,C_i}|C, IM]P(C|IM) \quad (8)$$

For the calculation of $E^{norm}[\theta_l^{T,C_i}|IM]$, the following assumptions are noteworthy:

- (I) $E^{norm}[\theta_l^{T,C_i}|IM]$ is calculated for a given building response (**EDP** $|IM$).
- (II) The **EDP** vectors are calculated for a given building of class i , (C_i) and a given value of ground motion IM , (**EDP** $|IM$) C_i .
- (III) The ground motion IM is obtained through Campbell and Bozorgnia [2008] ground motion prediction equations for a given site location and hazard specifications:
 - (a) Earthquake rupture parameters (e.g., Magnitude M_w).
 - (b) Site specification parameters (e.g., Shear-wave velocity V_s^{30}).
 - (c) Propagation effect parameters (e.g., Distance R), and
 - (d) $\epsilon(T_1)$, which is introduced by Baker and Cornell [2005], as a number of standard deviations by which an observed logarithmic spectral acceleration at period T_1 differs from the mean logarithmic spectral acceleration based on ground motion prediction equations.

The process for calculating $E^{norm}[\theta_l^{T,C_i}|IM]$ is as follows:

- (I) By performing Probabilistic Seismic Hazard Deaggregation (PSHD) for a particular site with corresponding V_s^{30} and given the probability of exceedance of ground motions over a certain period of exposure, the dominant seismic parameters $[R, M_w, \epsilon(T)]$ can be calculated. The USGS National Seismic Hazard Mapping Program Probabilistic Seismic Hazard Assessment Interactive Deaggregation tool (available at <http://earthquake.usgs.gov/hazards/>) may be used to obtain these parameters for sites within the United States.
- (II) Standard ground motion selection and modification (GMSM) methods may be utilized to find a set of horizontal ground motions that represents the hazard level considered for the PBSA. Addressing GSM methods is beyond the scope of this research. Commonly utilized hazard levels include the “design basis earthquake” (DBE) corresponding to ground motion level with a 10% probability of exceedance in 50 years, and “maximum considered earthquake” (MCE) corresponding

to 2% in 50 years exceedance probability. Readers refer to literature available on GSM, some of which is summarized in ATC-82 [2011].

- (III) Given basic information about the dynamic characteristics of the building and the ground motions obtained in Step II, $\mathbf{EDP}|IM$ vectors and $P(C|IM)$ may be computed using Nonlinear Response History Analysis (NRHA) of the building under the selected set of horizontal ground motions.
- (IV) PBSA can be estimated using Eq. (8), $E^{norm}[\theta_l^{T,C_i}|IM]$.

2.2. General Regional Seismic Loss Assessment (RSLA)

A resource-intensive approach for regional urban scale (e.g., Los Angeles County, see Fig. 1a) loss assessment consists of performing site-specific loss assessment for every single building in a target region. Given the large inventory of buildings in a typical urban region, site-specific loss assessment for the purpose of regional loss assessment is not economically feasible. In our proposed RSLA approach, buildings in the target region are divided into a certain number of classes; a representative of each class is placed on a grid in the target region and site-specific loss assessment is performed for (Site location (*Latitude, Longitude*), R, M_w) as described below. This approach generates a discrete map in the regional spatial domain (*Latitude, Longitude*) as shown in Fig. 1a. By performing a spatial interpolation over the scattered discrete map, a continuous regional loss information layer of building class i is created, as shown in Fig. 1b. Assume that the total number of possible building classes for the study region is Q . The complete RSLA information database is compiled by repeating the above procedure for all Q possible building classes, as shown in Fig. 1c. The regional expected loss of any subregion, θ_l^R , may be estimated using the RSLA database for the entire region along with the building class distribution of the subregion of interest using Eq. (9) (see Fig. 2), where, $\mathbf{N}_C$ is a building class distribution for a given subregion, $\mathbf{RC}_C$ is a vector of the corresponding replacement costs associated with each building class, and θ_l^{norm} is a vector of total expected normalized loss for all Q possible building classes in the region (Eqs. (10)–(12)).

Figure 1. (a) Region of interest (Los Angeles County), (b) continuous regional performance-based information layer of building class i , (c) RSLA performance-based information database for all the Q possible building classes in the region.

Figure 2. (a) Selected subregion, (b) building class distribution over the interested subregion, (c) θ_l^{norm} components based on RSLA performance-based information database for all the Q possible building classes in the region.

$$\theta_l^R = (\mathbf{N}_C \times \mathbf{RC}_C) \times \theta_l^{norm} = \sum_{r=1}^Q N_{c_r} \cdot RC_{c_r} \cdot E^{norm}[\theta_l^{T,C_r}|IM] \quad (9)$$

$$\mathbf{N}_C = \text{diag}(N_{c_1}, N_{c_2}, N_{c_3}, \dots, N_{c_i}, \dots, N_{c_{Q-1}}, N_{c_Q}) \quad (10)$$

$$\mathbf{RC}_C = \begin{pmatrix} RC_{c_1} \\ RC_{c_2} \\ RC_{c_3} \\ \vdots \\ RC_{c_i} \\ \vdots \\ RC_{c_{Q-1}} \\ RC_{c_Q} \end{pmatrix} \quad (11)$$

$$\theta_l^{norm} = \begin{pmatrix} E^{norm}[\theta_l^{T,C_1}|IM] \\ E^{norm}[\theta_l^{T,C_2}|IM] \\ E^{norm}[\theta_l^{T,C_3}|IM] \\ \vdots \\ E^{norm}[\theta_l^{T,C_i}|IM] \\ \vdots \\ E^{norm}[\theta_l^{T,C_{Q-1}}|IM] \\ E^{norm}[\theta_l^{T,C_Q}|IM] \end{pmatrix} \quad (12)$$

Depending on the number of representative building classes, the accuracy of numerical models, and the number of selected ground motions obtained from GSM, the NRHA step can become the most elaborate and time-consuming part of RSLA. NRHA is

conducted for a given number of ground motion sets obtained through GSM, which, in itself, is performed over sets of dominant seismic parameters $[R, M_w, \epsilon(T^*)]$ acquired for a given period, T^* . In other words, by decreasing the number of required dominant seismic parameters $[R, M_w, \epsilon(T^*)]$ and incorporating new PBSA techniques (e.g., Esmaili *et al.* (2015)), the time required for NRHA and RSLA completion decreases. Steps for exercising the proposed approach over Los Angeles County for earthquake hazard associated with 10% probability of exceedance in 50 years are presented below in sequential order:

- (I) Specify site locations: The study region (e.g., Los Angeles County, Fig. 3a) is gridded, with site location grid points.
- (II) Obtain V_s^{30} : For each site, local soil conditions including V_s^{30} values can be obtained from V_s^{30} classification maps (e.g. Wills *et al.* (2000)), Fig. 3b.
- (III) Perform PSHD: By conducting PSHD for all site locations chosen in Step I, with corresponding V_s^{30} obtained in Step II, and a given hazard level (i.e., here is DBE), the dominant seismic parameters $[R, M_w, \epsilon(T_{base})]$ contributing to the hazard at each site can be calculated using USGS 2008 NSHMP PSHA Interactive Deaggregation tool for Spectral Acceleration at given basic periods, $T_{base} = 0.2, 0.3, 0.5, 1.0, 2.0$ and 3.0 s (Fig. 3c).
- (IV) Define reference points of $[R, M_w, \epsilon(T_{base})]$: Based on overlaps between the (R, M_w) envelopes for two consecutive basic periods (Fig. 3d), the reference points for each basic period are selected, as shown in Table 1. Selection details are summarized by Esmaili [2014].
- (V) Calculate $\epsilon(T^*)$ to be used in GSM: The value of $\epsilon^* = f(r_k, m_j | T^*)$, at a given period T^* , is calculated by taking a weighted average of upper-bound and lower-bound values corresponding to the basic periods T_a and T_b , if $T_a < T^* < T_b$. (see Eq. (13), Fig. 4). $\epsilon(T^* = 0.6\text{s})$ is calculated as an example in Table 1, with $T_a = 0.5\text{s}$ and $T_b = 1.0\text{s}$.

$$\epsilon^*(T^*) = \frac{(T_b - T^*)f(r_k, m_j | T_a) + (T^* - T_a)f(r_k, m_j | T_b)}{(T_b - T_a)} \quad (13)$$

Steps (I–V) will generate the required $[R, M_w, \epsilon(T^*)]$ triples to cover the whole region to be used for GSM. A comparison between number of reference points for $T^* = 0.6$ s in Table 1, and the corresponding number acquired from site-to-site PSHD over the whole region, highlights the effectiveness of the proposed approach in reducing the number of NRHA runs by about 30%. By conducting RSLA for the selected reference triples and utilizing the surface fitting (e.g., MATLAB toolbox, Mathworks (2013)) for linear interpolation, $E^{norm}[\theta_l^{T, C_i} | IM]$, the linear surface fitted on $[R, M_w, \epsilon(T^*)]$, can be obtained, represented by Eq. (14). By performing site-specific PSHD, a set of $[R, M_w, \epsilon(T)]$ is obtained for each site. Consequently, the total expected normalized loss value for each site can be calculated using Eq. (14).

$$E^{norm}[\theta_l^{T, C_i} | IM] = h(R, M_w, \epsilon(T^*)) \quad (14)$$

(c) Dominant $[R, M_w, \varepsilon(T_{base})]$ acquired by USGS 2008 NSHMP PSHA Interactive Deaggregation tool.

(b) Soil type map

(a) Site locations (Lat. & Long.)

(d) Mean value envelopes $[R, M_w, \varepsilon(T_{base})]$

Mean value envelopes for dominant $[R, M_w, \varepsilon(T_{base})]$ based on PSH Deaggregation Comparison on NEHRP, Soil Type D, for Spectral Acceleration values at all base periods for a given hazard level. (Reference points are in squares).

$$\varepsilon^* = \frac{(T_b - T^*)f(r_k, m_j | T_a) + (T^* - T_a)f(r_k, m_j | T_b)}{(T_b - T_a)}$$

(e) Selected reference values for $[R, M_w, \varepsilon^*(T^*)]$ at all base periods (T_a and T_b) for a given hazard level.

Figure 3. (a) Representative site locations at grid points. (b) Soil type and corresponding V_s^{30} values for the interested locations. (c) Mean ($R = r_k, M_w = m_j, \varepsilon_0$) for basic periods (T_a and T_b) for a given hazard level based on USGS 2008 NSHMP PSHA Interactive Deaggregation tool for a given hazard level (e.g., DBE or MCE). (d) Mean value envelopes for dominant $[R, M_w, \varepsilon(T_{base})]$ based on PSH Deaggregation Comparison on NEHRP, Soil Type D, for Spectral Acceleration values at all base periods for a given hazard level, (Reference points are in squares). (e) $\varepsilon^* = f(r_k, m_j | T^*)$ for a given period T^* , is calculated by a weighted average of upper and lower planes corresponding to the basic periods T_a and T_b , if $T_a < T^* < T_b$.

2.3. Example application of RSLA in Los Angeles County

The proposed RSLA approach introduced in the preceding section has been applied to Los Angeles County at the design-level earthquake hazard (DBE) and will be discussed as a case study in this section. A key component for the successful

Table 1. Selected reference $[R, M_w, \varepsilon(T_{base})]$ triples based on PSH deaggregation comparison on NEHRP Soil D (top section from a-to-w) and Soil CD (bottom section from a-to-j) at each basic period at DBE hazard level.

Point	R	M	ε					ε
			$T = 0.2 \text{ s}$	$T = 0.3 \text{ s}$	$T = 0.5 \text{ s}$	$T = 1.0 \text{ s}$	$T = 2.0 \text{ s}$	$T = 0.6 \text{ s}$
a	8.8	6.576	0.675	0.625				
b	15.1	6.576	0.825	0.775				
c	21.4	6.576	1.025	0.825				
d	7.2	6.724	0.675	0.625	0.478	0.525		0.487
e	13.5	6.724	0.875	0.900	0.643	0.525		0.619
f	19.8	6.724	1.025	0.850	0.863	0.575		0.805
g	26.1	6.724	1.025	0.975	0.863	0.625		0.815
h	11.9	6.872	0.675	0.625	0.753	0.775	0.725	0.757
i	18.2	6.872	0.800	0.700	0.808	0.800	0.725	0.806
j	24.5	6.872	1.025	0.775	0.863	0.775	0.725	0.845
k	30.8	6.872			0.863	0.750	0.750	0.840
l	16.6	7.020			0.753	0.825	0.825	0.767
m	22.9	7.020			0.753	0.725	0.925	0.747
n	29.2	7.020			0.753	0.875	0.875	0.777
o	35.5	7.020				0.875	0.875	
p	21.3	7.168				0.675	1.000	
q	27.6	7.168				0.675	0.950	
r	33.9	7.168				0.725	1.175	
s	40.2	7.168				0.875	0.975	
t	26.0	7.316				0.625	0.975	
u	32.3	7.316				0.625	0.850	
v	38.6	7.316				0.625	0.725	
w	44.9	7.316				0.875	0.850	
a	7.5	6.580	0.550	0.575	0.500	0.515		0.530
b	13.2	6.580	0.650	0.575	0.500	0.615		0.523
c	18.9	6.580	0.775	0.575	0.500	0.665		0.533
d	5.0	6.750	0.600	0.575	0.450	0.615		0.483
e	10.7	6.750	0.550	0.700	0.630	0.440		0.592
f	16.4	6.750	0.675	0.625	0.580	0.465		0.557
g	22.1	6.750	0.800	0.800	0.500	0.665		0.533
h	8.0	6.920	0.550	0.525	0.430	0.415		0.427
i	13.7	6.920	0.550	0.550	0.440	0.415		0.435
j	19.4	6.920	0.725	0.750	0.620	0.415		0.579

application of RSLA is generating the database of all possible building classes located in Los Angeles. A generic set of four-story three-bay reinforced concrete office buildings with a square plan in each direction are used in this study. These buildings include a variety of structural and nonstructural components to cover probable representative reinforced concrete building classes in the Los Angeles County region.

2.4. Building characteristics and structural modeling

All building classes have story heights of 15 feet in the first story (h_{base}) and 13 feet otherwise. For a given building bay spans are equal, and three sizes are considered: 22.5, 30, or 37.5 feet based on $1.5 h_{base}$, $2.0 h_{base}$, and $2.5 h_{base}$, respectively. The frames are designed according to the performance-based plastic design concepts for the first mode period proportionate to the number of stories by α_T , which varies between 0.15, 0.20, and 0.25. Therefore, as $T_1 = \alpha_T N$, the range for the first mode period is $T_1 = 0.6, 0.8$, and 1.0 s . Variation of floor mass along the height is assumed to be uniform, while story stiffness

Figure 4. Example showing calculation of $\varepsilon^* = f(r_k, m_j | T^*)$ at a given period T^* .

varies along the height where a straight-line deflected shape is obtained under the American Society of Civil Engineers (ASCE) 7–10 [2010] lateral load pattern. The strong-column, weak-beam design approach is also considered for all frames. Open System for Earthquake Engineering Simulation (OpenSees, 2012, version 2.3.2) is used as the main structural analysis platform for numerical modeling and analysis of the generic frames, as illustrated in Fig. 5. In the modeling phase, it is assumed that flexural nonlinear behavior is

Figure 5. (a) Schematic concentrated plasticity OpenSees model of four-story RCMF structural analysis model and the leaning P-Delta columns. (b) Backbone curve definition based on typical modified Ibarra-Krawinkler-Medina deterioration model where K_e is the initial stiffness, M_y is the yield moment, and M_c/M_y is the capping moment ratio.

concentrated at the ends of the beams and columns. The backbone curve for stiffness and strength of the frame is illustrated in Fig. 5. The component model used in this study is a modified version of the component deterioration model proposed by Ibarra and Krawinkler [2005], named modified Ibarra–Krawinkler–Medina (IKM) deterioration model [Ibarra and Krawinkler, 2005; Lignos and Krawinkler, 2009], Fig. 5. This component model incorporates strength and stiffness deterioration based on the hysteretic energy dissipated when the component is subjected to cyclic loading [Zareian and Krawinkler, 2007].

Cyclic deterioration of strength and stiffness is based on a reference hysteretic energy dissipation capacity, $E_t = \lambda M_y \theta_p$ where λ is a parameter that is estimated using experimental results [Haselton *et al.*, 2006; Lignos and Krawinkler, 2009]. Plastic hinge rotation capacity, θ_p , post-capping rotation capacity, θ_{pc} , and cyclic deterioration parameter, λ , of beams and columns are set to corresponding median values. Tenth and ninetieth percentile of the lognormal distributions are fitted on the parameter values obtained based on the research done by Berry *et al.* [2004] and calibrated by Haselton *et al.* [2006], as shown in Fig. 6.

It is assumed that the generic RCMFs used in this study are not expected to carry a large portion of the gravity load of the building and are primarily used for the lateral load resisting system. Therefore, in data processing, specimens with an axial load ratio, ν , less than 0.2 are chosen for statistical evaluation. Also, shear failure is not considered because it is assumed that none of the structural components in the selected generic frames are shear critical. Rayleigh damping corresponding to 5% of the critical damping in the first and third modes is applied. Destabilizing P-Delta effects due to gravity loads are also considered. All 27 combinations of RCMFs used in this study are illustrated in Fig. 7. Each cross-path in Fig. 7 represents one building class.

3. Result: RSLA performance-based information database

The PSHD is performed according to the procedure illustrated in Fig. 3 for the DBE hazard level. Subsequently, the GSM procedure described in Jayaram *et al.* [2010] is performed for each reference $[R, M_w, \epsilon(T^*)]$ obtained from PSHD in order to select a set of 20 horizontal ground motions per each reference point. With the selected ground motions from the GSM phase, NRHA is conducted with building numerical models in OpenSees to compute **EDP** vectors for each building class. Ultimately, the Seismic Assessment tool For Earthquake loss Rating (SAFER), an in-house loss estimation tool [Esmaili, 2014], is used to quantify losses given the **EDP** vectors obtained in the previous step. SAFER is developed using MATLAB [MathWorks, 2013] to estimate $E^{norm}[\theta_l^{T,C_i}|IM]$, given the calculated $(\mathbf{EDP}|IM)$ vectors for each reference $[R, M_w, \epsilon(T^*)]$. These vectors are obtained from PSHD using a full Monte Carlo probabilistic simulation over story-based generic EDP -DV functions. Correlations between $(\mathbf{EDP}|IM)$ components in horizontal directions are considered for this process. This is a major difference between SAFER and common loss estimation tools such as the Performance Assessment Calculation Tool (PACT) [ATC, 2012]. Readers can find a detailed description of SAFER in Esmaili [2014]. With Eq. (14), $E^{norm}[\theta_l^{T,C_i}|IM]$ values are estimated for each site. By performing spatial interpolation over the scattered discrete $\{E^{norm}[\theta_l^{T,C_i}|IM].Latitude.Longitude\}$ map, continuous regional performance-based information layers of all building classes are created (e.g., Figs. 8 and 9).

Figure 6. Range of variations for structural component parameters: θ_p , θ_{pc}/θ_p , λ and M_c/M_y used in modified Ibarra–Krawinkler–Medina deterioration model and the selected values (data from Haselton et al., 2006).

Figure 7. All RCMF classes used in this study. The heavy line represents a building class with the parameter values shown.

Figure 8. RSLA information layer at DBE level for a building with $T = 1.0 \text{ s}$, $\gamma = 0.7$, $\theta_p = 0.03$.

Figure 9. RSLA information layers at DBE level for buildings with variation in T and γ and $\theta_p = 0.03$.

Figure 9 and those similar to it in Esmaili [2014] show the sensitivity of loss to building characteristics. For instance, in a building with relatively high stiffness (here $T = 0.6$ s), it is expected to see a larger amount of loss from acceleration-sensitive components compared to drift-sensitive ones. Therefore, losses in such buildings exhibit an inversely proportional relationship with γ . On the flip side, when a building is relatively flexible (here $T = 1.0$ s), drift-sensitive components dominate the losses and have a direct correlation with γ . Variation in structural components (θ_p , θ_{pc}/θ_p , λ) and l/h_{base} also have minor effects on the total building loss at DBE hazard level; a complete description of similar results are presented in Esmaili [2014].

In accordance with the preceding discussion, and to simplify the example, we assume all buildings in Los Angeles County can be categorized with three classes: C_1 : $T = 0.6$ s, $\gamma = 0.7$, $\theta_p = 0.03$; C_2 : $T = 0.8$ s, $\gamma = 0.7$, $\theta_p = 0.03$; and C_3 : $T = 1.0$ s, $\gamma = 0.7$, $\theta_p = 0.03$ (Fig. 10a–c). To apply Eq. (9), we also assume that all the building classes have the same value; consequently, $\mathbf{RC}_C$ is a uniform vector.

By putting a grid over the area (e.g., 200×200 cells, one cell is highlighted in Fig. 10e), $\mathbf{N}_C$ can be defined based on the building class distribution within each cell (Fig. 10d), with various colors (e.g., normalized loss color scale) representing each

Figure 10. Regional performance-based information layers at DBE hazard level for RCMF's normalized expected loss, for corresponding first mode period (T), drift-sensitive components' contribution coefficient (γ), and structural component parameters: $\theta_p, \theta_{pc}/\theta_p, \lambda$, for a constant $l/h_{base} = 2.5$, (a) for $T = 0.6$ s, $\gamma = 0.7$, $\theta_p = 0.03$, (b) $T = 0.8$ s, $\gamma = 0.7$, $\theta_p = 0.03$ and (c) $T = 1.0$ s, $\gamma = 0.7$, $\theta_p = 0.03$, (d) spatial distribution of the example building classes within the subregion, (e) aggregated θ_l^R based on RSLA performance-based information database of all the example building classes within the subregion.

building class. With Eq. (9), the regional normalized loss index may be calculated (see Figs. 10 and 11).

The purpose of the above example is to show what the possible outcomes of RSLA methodology look like. Bounded RSLA maps are one of the useful products of RSLA, in addition to RSLA information layers for decision makers. RSLA maps are developed through a screening process for the loss level of interest (e.g., here is 15%) over the general RSLA database (e.g., Fig. 11). Decision makers can initiate risk mitigation plans according to the vulnerable zones outlined by bounded RSLA maps. Figure 12 shows such a map for the Los Angeles case study; vulnerable zones for losses beyond 15% and the total cost at DBE hazard level are highlighted for the assumed three building classes only. The potential earthquake loss hotspots for the selected building classes are illustrated in Fig. 12. Accordingly, the best places to start seismic retrofitting of the selected building classes are the three zones shown in Fig. 12. The map in Fig. 12 is developed using an assumed distribution of building stock and uniform building value distribution. Having such a map

Figure 11. Example RSLA map for Los Angeles County and zonation at DBE hazard level for the selected RCMF's classes. (This map is just an example and should not be used for engineering purposes).

Figure 12. Example potential vulnerable zones with $15\% < \theta_l^R$ at DBE hazard level for the selected RCMF's classes based on RSLA map for Los Angeles County. (This map is just an example and should not be used for engineering purposes).

based on real data can help stakeholders make informed decision regarding the allocation of resources for retrofit and the development of emergency response plans.

4. Summary and future studies

This study is devoted to the formulation and construction of a rapid integrated regional earthquake loss assessment method for buildings. As a case study, a hazard-based general RSLA of buildings is presented for a range of four-story reinforced concrete moment-resisting frame buildings in Los Angeles County with a ground motion return period of 475 years (10% chance of exceedance in 50 years, or DBE). Other important seismically active areas in the United States such as northern California, Oregon, and Washington, can be evaluated with RSLA methodology relatively quickly and with less computational effort than other methods if the basic performance information input layers have been developed. This procedure also requires obtaining regional statistical information for building inventories. With the required statistical information, the next step is to create *EDP-DV* functions for corresponding structural systems. Through RSLA, other loss components, such as downtime, can be also regionally estimated. Moreover, as the RSLA method is a hazard-based regional loss assessment methodology, performance information layers could be developed for other hazard levels such as SLE25, SLE43 that correspond to “strength-level earthquakes” with return periods of 25, 43 and for MCE level with 2475 years, respectively. This would allow RSLA to be applied broadly at different hazard levels.

ORCID

Lisa Grant Ludwig <http://orcid.org/0000-0001-6538-8067>

References

- American Society of Civil Engineers (ASCE). [2010] *Minimum Design Loads for Buildings and Other Structures*, ASCE 7–10, Reston, VA.
- Applied Technology Council (ATC). [2011] *Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses*, PEER/ATC 82. Redwood City, California.
- Baker, J. W. and Allin Cornell, C. [2005] “A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon,” *Earthquake Engineering and Structural Dynamics* **34**(10), 1193–1217.
- Barbat, A. H., Moya F. Y. and Canas J. A. [1996] “Damage scenarios simulation for seismic risk assessment in urban zones,” *Earthquake Spectra* **12**(3), 371–394.
- Berry, M., Parrish, M. and Eberhard, M. [2004] *PEER Structural Performance Database User’s Manual*, Pacific Engineering Research Center, University of California.
- Bazzurro, P. and Luco, N. [2005] “Accounting for uncertainty and correlation in earthquake loss estimation,” *Proc. ICOSSAR2005*.
- Campbell, K. W. and Bozorgnia, Y. [2008] “NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s,” *Earthquake Spectra* **24**(1), 139–171.
- Chang, S. E., Shinozuka, M. and Moore, J. E. [2000] “Probabilistic earthquake scenarios: extending risk analysis methodologies to spatially distributed systems,” *Earthquake Spectra* **16**(3), 557–572.

- Cornell, C. A. and Krawinkler, H. [2000] "Progress and challenges in seismic performance assessment," *Pacific Earthquake Research Center News*, **3**(2).
- Couture, R., Evans, S. G. and Locat, J. [2002] "Introduction, natural hazards in Canada", *Natural Hazards*, **26**(1–6).
- Crowley, H. and Bommer, J. J. [2006] "Modelling seismic hazard in earthquake loss models with spatially distributed exposure," *Bulletin of Earthquake Engineering* **4**(3), 249–273.
- Daniell, J. E. [2009] "Open source procedure for assessment of loss using global earthquake modelling (OPAL-GEM Project): CEDIM Research Report 2009-01," *CEDIM Loss Estimation Series*, Karlsruhe, Germany.
- Daniell, J. E. [2011] "Open source procedure for assessment of loss using global earthquake modelling software (OPAL)." *Natural Hazards and Earth System Sciences* **7**(7), 1885–1899.
- DeBock, D. J., Kim, K. Y. and Liel, A. B. [2013] "A Scenario Case Study to Evaluate Methods of Seismic Loss Assessment for Communities of Buildings: Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures," CRC Press 2014, pp. 789–796. doi: [10.1201/b16387-114](https://doi.org/10.1201/b16387-114).
- DeBock, D. J., Garrison, J. W., Kim, K. Y. and Liel, A. B. [2014] "Incorporation of spatial correlations between building response parameters in regional seismic loss assessment," *Bulletin of the Seismological Society of America* **104**(1), 214–228.
- Deierlein, G. G. [2004] "Overview of a comprehensive framework for earthquake performance assessment," *Proceedings of International Workshop on Performance-Based Seismic Design Concepts and Implementation*, Bled, Slovenia.
- Du, W. and Wang, G. [2013] "Intra-event spatial correlations for cumulative absolute velocity, arias intensity, and spectral accelerations based on regional site conditions," *Bulletin of the Seismological Society of America* **103**(2A), 1117–1129.
- Ebel, J. E. and Kafka, A. L. [1999] "A Monte Carlo approach to seismic hazard analysis," *Bulletin of the Seismological Society of America* **89**(4), 854–866.
- Esmaili, O. [2014] "Developing a Rapid Seismic Performance based Rating System in Safety Assessment of Buildings," University of California: Irvine.
- Esmaili, O., Grant Ludwig, L. and Zareian, F. [2015] "Improved performance-based seismic assessment of buildings by utilizing bayesian statistics," *Journal of Earthquake Engineering and Structural Dynamics*. doi:[10.1002/eqe.2672](https://doi.org/10.1002/eqe.2672).
- Esposito, S. and Iervolino, I. [2011] "PGA and PGV spatial correlation models based on European multievent datasets," *Bulletin of the Seismological Society of America* **101**(5), 2532–2541.
- Federal Emergency Management Agency (FEMA). [1999] "HAZUS99 Technical Manual," Federal Emergency Management Agency: Washington, DC, U.S.A.
- Federal Emergency Management Agency (FEMA). [2001] "HAZUS99 Estimated Annualized Earthquake Loss for the United States," Report FEMA 366, Federal Emergency Management Agency: Washington, DC, U.S.A.
- Federal Emergency Management Agency (FEMA). [2003] "HAZUS-MH Technical Manual," Federal Emergency Management Agency: Washington, DC, U.S.A.
- Federal Emergency Management Agency (FEMA). [2006] "FEMA 445: Next-Generation Performance-Based Seismic Design Guidelines," Federal Emergency Management Agency: Washington, D.C.
- Federal Emergency Management Agency (FEMA P-58-1) (ATC-58). [2012] "Guidelines for Seismic Performance Assessment of Buildings, Volume 1 – Methodology," Redwood City, California.
- Goda, K. and Hong, H. P. [2008a], "Estimation of seismic loss for spatially distributed buildings," *Earthquake Spectra* **24**(4), 889–910.
- Goda, K. and Hong, H. P. [2008b], "Spatial correlation of peak ground motions and response spectra," *Bulletin of the Seismological Society of America*, **98**(1), 354–365.
- Goda, K. and Atkinson, G. M. [2009] "Probabilistic characterization of spatially correlated response spectra for earthquakes in Japan," *Bulletin of the Seismological Society of America*, **99**, 3003–3020.
- Haselton, C. B. [2006] "Assessing seismic collapse safety of modern reinforced concrete moment frame buildings," Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University.

- Haselton, C. B., Liel, A. B., Taylor, L. S. and Deierlein, G. G. [2006] “*Beam-Column element model calibrated for predicting flexural response leading to global collapse of RC frame buildings*,” PEER Report, Pacific Earthquake Research Center, University of California at Berkeley: Berkeley, California.
- Ibarra, L. F. and Krawinkler, H. [2005] “*Global collapse of frame structures under seismic excitations*,” Technical Report 152, The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University: Stanford, CA.
- Jayaram, N. and Baker, J. W. [2009] “Correlation model for spatially distributed ground-motion intensities,” *Earthquake Engineering and Structural Dynamics* **38**(15), 1687–1708.
- Jayaram, N., Lin, T. and Baker, J. W. [2011] “A computationally efficient ground-motion selection algorithm for matching a target response spectrum mean and variance,” *Earthquake Spectra* **27** (3), 797–815.
- Krawinkler, H. [2002] “A general approach to seismic performance assessment,” *Proceedings, International Conference on Advances and New Challenges in Earthquake Engineering Research*, ICANCEER 2002, Hong Kong, August 19–20.
- Krawinkler, H. and Miranda, E. [2004] Performance-based earthquake engineering, in *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*, eds. Y. Bozorgnia and V. V. Bertero, CRC Press: Boca Raton.
- Krawinkler, H., Zareian, F., Medina, R. A. and Ibarra, L. F. [2006] “Decision support for conceptual performance-based design,” *Earthquake Engineering and Structural Dynamics* **35**(1), 115–133.
- Lee, R. and Kiremidjian, A. S. [2007] “Uncertainty and correlation for loss assessment of spatially distributed systems,” *Earthquake Spectra* **23**(4), 753–770.
- Lignos, D. G. and Krawinkler, H. [2009] “*Side sway collapse of deteriorating structural systems under seismic excitations*,” Technical Report 172, The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University: Stanford, CA.
- Loth, C. and Baker, J. W. [2013] “A spatial cross-correlation model of spectral accelerations at multiple periods,” *Earthquake Engineering and Structural Dynamics* **42**(3), 397–417.
- Mathworks. [2013] Available online: <http://www.mathworks.com/>. (Date of last access: 20 January, 2014)
- Miranda, E. and Aslani, H. [2003] “*Probabilistic response assessment for building-specific loss estimation*,” PEER report 2003/03, Pacific Earthquake Research Center, University of California at Berkeley: Berkeley, California.
- Molina, S. and Lindholm, C. [2005] “A logic tree extension of the capacity spectrum method developed to estimate seismic risk in Oslo, Norway,” *Journal of Earthquake Engineering* **9**(6), 877–897.
- Open System for Earthquake Engineering Simulation (OpenSees). [2012] “*Pacific Earthquake Engineering Research Center*, Univ. of California: Berkeley, CA. Available online: <http://opensees.berkeley.edu/>. (Date of last access: 15 January, 2014)
- Park, J., Bazzurro, P. and Baker, J. W. [2007] Modeling spatial correlation of ground motion intensity measures for regional seismic hazard and portfolio loss estimation, in *Applications of Statistics and Probability in Civil Engineering*, Taylor & Francis Group: London, pp. 1–8.
- Performance Assessment Calculation Tool (PACT), Federal Emergency Management Agency (FEMA), Applied Technology Council (ATC). [2012] *FEMA P-58-1 (ATC-58), Guidelines for Seismic Performance Assessment of Buildings, Volume 1 – Methodology*, Redwood City, California.
- Ramirez, C. M. and Miranda, E. [2009] “*Building-specific loss estimation methods & tools for simplified performance-based earthquake engineering*,” John A. Blume Earthquake Engineering Center, Report No. 171.
- Shiraki, N., Shinozuka, M., Moore, J. E., Chang, S. E., Kameda, H. and Tanaka, S. [2007] “System risk curves: probabilistic performance scenarios for highway networks subject to earthquake damage,” *Journal of Infrastructure Systems* **13**(1), 43–54.
- Sokolov, V., Wenzel, F., Jean, W. Y. and Wen, K. L. [2010] “Uncertainty and spatial correlation of earthquake ground motion in Taiwan,” *Terrestrial, Atmospheric and Oceanic Sciences* **21**, 905.

- Sousa, M. L., Campos Costa, A., Carvalho, A. and Coelho, E. [2004] "An automatic seismic scenario loss Methodology integrated on a geographic information system," *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada.
- Strasser, F. O., Stafford, P. J., Bommer, J. J. and Erdik, M. [2008] "State-of-the-art of european earthquake loss estimation software," *Proceedings of the 14th WCEE*, Beijing, China.
- Tesfamariam, S. and Liu, Z. [2010] "Earthquake induced damage classification for reinforced concrete buildings," *Structural Safety* **32**, 154–164.
- U.S. Geological Survey (USGS). [2008] "NSHMP PSHA Interactive Deaggregation tool." Available online: <http://geohazards.usgs.gov/deaggint/2008/>. (Date of last access: 14 January, 2014)
- Vaziri, P., Davidson, R., Apivatanagul, P. and Nozick, L. [2012] "Identification of optimization-based probabilistic earthquake scenarios for regional loss estimation," *Journal of Earthquake Engineering* **16**(2), 296–315.
- Wang, M. and Takada, T. [2005] "Macrospatial correlation model of seismic ground motions," *Earthquake Spectra* **21**(4), 1137–1156.
- Werner, S. D., Taylor, C. E., Cho, S., Lavoie, J. P., Huyck, C. K., Eitzel, C. and Eguchi, R. T. [2006] "Redars 2 methodology and software for seismic risk analysis of highway systems" (No. MCEER-06-SP08).
- Wesson, R. L. and Perkins, D. M. [2001] "Spatial correlation of probabilistic earthquake ground motion and loss," *Bulletin of the Seismological Society of America* **91**(6), 1498–1515.
- Whitman, R. V., Anagnos, T., Kircher, C. A., Lagorio, H. J., Lawson, R. S. and Schneider, P. [1997] "Development of a national earthquake loss estimation methodology," *Earthquake Spectra* **13**(4), 643–661.
- Wills, C. J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G. J., Tan, S. and Treiman, J. [2000] "A site-conditions map for California based on geology and shear-wave velocity," *Bulletin of the Seismological Society of America* **90**(6B), S187–S208.
- Zareian, F. and Krawinkler, H. [2007] "Sensitivity of collapse potential of buildings to variations in structural systems and structural parameters," *Proceedings of the 2007 Structures Congress*, Long Beach, CA.