Risk, Resilience, and Sustainability Assessment of Infrastructure Systems in a Life-Cycle Context Considering Uncertainties

You Dong
Graduate Student, Dept. of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, USA

Dan M. Frangopol
Professor, Dept. of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, USA

ABSTRACT: Within a life-cycle context, infrastructure systems may be subjected to abnormal events, which can hamper functionality of these systems. Maintaining functionality of highway bridges under hazard effects is gaining increased attention. In this paper, a framework for performance assessment of highway bridges under seismic hazard considering risk and resilience is presented. The time effects and uncertainties are integrated within the proposed seismic risk and resilience assessment procedure. Overall, the risk and resilience assessment of a bridge under seismic activity is based on a set of damage states, which are mutually exclusive and collectively exhaustive. Additionally, the probabilistic direct loss, indirect loss, and resilience of a bridge under seismic hazard are investigated. Sustainability assessment of highway bridges is also investigated. The assessment of probabilistic risk, resilience, and sustainability of highway bridges under seismic hazard can aid in implementing risk-informed seismic mitigation and equip decision makers with a better understanding of structural seismic performance in a life-cycle context. The proposed methodology is illustrated on an existing bridge located in California.

1. INTRODUCTION

Infrastructure systems may be subjected to extreme events such as floods, earthquakes, and fires during their service life. Highway bridges play an important role in the sustained economic growth and social development of most countries. Maintaining functionality of highway bridges under hazard effects is gaining increased attention. According to the United States Geological Survey (USGS) (2003), there is a 0.62 probability of a strong earthquake (i.e., moment magnitude ≥ 6.7) striking the San Francisco Bay Region (SFBR, California) during the period from 2003 to 2032 (USGS 2003). This highlights the necessity of effective assessment of structural seismic performance. Overall, seismic risk and resilience assessment is of vital importance to ensure structural safety and functionality during service life of infrastructure systems.

Risk-based performance indicators combine the probability of structural failure with the consequences associated with a particular failure event (Ellingwood 2005; Frangopol 2011; Saydam *et al.* 2013; Barone and Frangopol 2014). Regarding the consequence evaluation process, sustainability includes social, economic, and environmental metrics in order to effectively represent structural performance and can serve as a useful tool in decision making associated with civil infrastructure systems (Adams 2006; Dong *et al.* 2014). Sustainability assessment of highway bridges under seismic hazard is emphasized in this study. Resilience is another important structural performance indicator that accounts for structural performance and recovery patterns under extreme events (Bruneau *et al.* 2003; Frangopol and Bocchini 2011; Bocchini *et al.* 2014). The resilience indicator measures a structure's ability to restore its full functionality after an extreme event. It is critical that the quantification of seismic risk and resilience at the holistic level be processed through a probabilistic framework to account for and incorporate all relevant uncertainties.

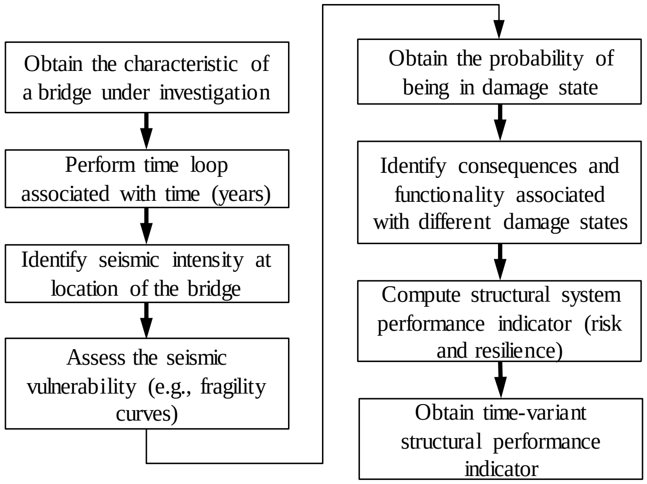

Figure 1. Flowchart of time-variant structural performance assessment process under seismic hazard

Generally, the seismic performance of a bridge deteriorates with time. The time effects should be considered in the life-cycle seismic loss assessment process. As a result, the seismic risk increases with time (Decò and Frangopol 2013; Dong *et al.* 2013). The life-cycle seismic loss is a rational performance indicator. Within relevant published literature, only few studies have quantified the life-cycle seismic loss considering time effects. Moreover, to the best of the authors' knowledge, there is no study that assesses the time-variant resilience of highway bridges under seismic hazard. In this paper, the time-variant risk and resilience of highway bridges under seismic hazard are both considered in a life-cycle context. The flowchart regarding the assessment of time-variant seismic performance indicators (e.g., risk and resilience) is shown in Figure 1.

In this paper, a framework for time-variant risk and resilience assessment of highway bridges subjected to hazard effects is presented. Additionally, the life-cycle seismic loss without and with time effects is also computed. The evaluation of seismic loss and functionality of a bridge under seismic scenarios is based on a set of damage states, which are mutually exclusive and collectively exhaustive. The uncertainties associated with seismic scenarios, seismic vulnerability analysis, and consequence evaluation are incorporated within this framework. The proposed framework is applied to an existing bridge located in California. This paper aims to not only quantify the seismic risk and resilience of a bridge, but also to investigate the aging effects on life-cycle seismic loss. Ultimately, the probabilistic assessment of life-cycle risk and resilience of bridges can aid the decision maker to implement optimal seismic design and mitigation strategies.

2. PROBABILISITIC SEISMIC VULNERABILITY ANALYSIS

The first step in seismic vulnerability assessment is to identify the seismic intensity associated with the location of the structural system under investigation. A specific number of seismic scenarios should be generated within the region of interest. The generated scenarios should be able to approximate the actual seismic activity of the geographical area. Subsequently, an attenuation equation is used to predict the ground-motion intensity at a certain location (Campbell and Bozorgnia 2007). More detailed information regarding the generation of probabilistic seismic scenarios can be found in Dong *et al.* (2014).

The next step is to compute the vulnerability of structural systems under seismic hazard. Fragility curves are commonly used to predict structural performance under seismic hazard. Due to time effects, the fragility curves should be evaluated throughout the lifetime of a structure. The time-variant fragility curves can be computed as (Decò and Frangopol 2013; Dong *et al.* 2013)

$$P_{S\geq DS_i|IM}(t) = \Phi(\frac{\ln(IM)-\ln(m_i(t))}{\beta_i(t)}) \qquad (1)$$

where $\Phi(.)$ is the standard normal cumulative distribution function; IM is the seismic intensity measure (e.g., peak ground acceleration (PGA), spectral acceleration amplitude); $\beta_i(t)$ is the standard deviation of the damage state i of the structural fragility at time t; and m_i is the median value of ground motion intensity associated with damage state i.

3. LIFE-CYCLE SEISMIC RISK ASSESSMENT

The risk assessment of structural systems under seismic hazard is presented in this section. The risk can be computed as the product of probability of failure and consequence of this event. The probability of a structural system being in different damage states can be computed on basis of fragility curves, as described in the previous section. The repair loss (i.e., direct loss) due to the failure of a structure may be relatively high, while the non-functionality of bridges can bring even more disastrous consequences. The sustainability metrics (i.e., economic, social, and environmental) of structural systems under seismic hazard are computed in order to cover a broad performance assessment. The time-variant metric of sustainability, in its general form, can be expressed as (Ellingwood 2005)

$$S_{Metric}(t) = \sum\nolimits_H \sum\nolimits_{DS} C_{Cons|DS}(t) \cdot P_{DS|H}(t) \cdot P_H(t) \tag{2}$$

where $C_{Cons|DS}(t)$ is the conditional consequence (e.g., economic, social, and environmental) given a damage state (e.g., slight, moderate, major, complete) at year t; $P_{DS|H}(t)$ is the conditional probability of a damage state given a hazard at time t; and $P_H(t)$ is the annual mean rate of occurrence of hazard H at time t. Based on the theorem of total probability, the total sustainability is the sum of consequences weighted with the probability of having these consequences associated with damage states.

Generally, there are both aleatoric and epistemic uncertainties involved in hazard assessment and consequence evaluation associated with these probabilistic seismic scenarios. These uncertainties should be considered in this probabilistic sustainability assessment framework. Given the distribution parameters, these random variables can be generated using MATLAB (MathWorks 2013). By performing numerical simulation, the expected value and dispersion of the sustainability metrics can be obtained throughout the service life of the structural systems.

The consequences associated with each damage state of a bridge should be evaluated in terms of monetary value. For example, the repair loss associated with a certain damage state can be considered proportional to the rebuilding cost of a bridge and expressed as (Mander 1999)

$$L_{REP}(t) = \sum_{i=1}^{4} RCR_i \cdot c_{REB} \cdot W \cdot L \cdot P_{S=DS_i|IM}(t) \tag{3}$$

where RCR_i is the repair cost ratio for a bridge in damage state i; c_{REB} is the rebuilding cost per square meter (USD/m^2); W is the bridge width (m); L represents the bridge length (m); and $P_{S=DSi|IM}$ is the conditional probability of the bridge being in damage state i under given seismic intensity at time t. The total seismic loss is computed by summing up all the metrics associated with repair, time, fatalities, operating, and environmental losses. The annual total seismic loss can be computed as

$$L_{tot}(t) = L_{REP}(t) + L_{OL}(t) + L_{TL}(t) + L_{FA}(t) + L_{ENV}(t) \tag{4}$$

where L_{REP} is repair loss; L_{OL} is operation loss; L_{TL} is time loss; L_{FA} is fatalities loss; and L_{ENV} is environmental loss of a bridge under seismic hazard. More detailed information regarding social and environmental metrics assessment of highway bridges under seismic hazard can be found in Dong *et al.* (2013) and Dong and Frangopol (2015).

Considering the time effects on seismic performance of a bridge, the life-cycle seismic risk can be computed as (Yeo and Cornell 2005)

$$LCL_{Seis} = \sum_{i=1}^{N(T_{\text{int}})} L_{k,tot}(t_k) \cdot e^{-rt_k} \tag{5}$$

where T_{int} is investigated time interval; $N(T_{int})$ is the random number of seismic events that occur during time interval T_{int} and expected value of $N(T_{int})$ equals λT_{int}; λ is the mean occurrence rate of seismic hazard; $L_{k,tot}(t_k)$ is the expected total seismic loss at time t_k under seismic hazard k; and r is the constant monetary discount rate. The occurrence of earthquake is modeled by a homogeneous Poisson process with rate λ. The relation between $L_{k,tot}$ and time t can be computed on basis on Eq. (5). Subsequently, the life-cycle seismic loss can be computed.

4. SEISMIC RESILIENCE ASSESSMENT

The functionality of a bridge under seismic hazard is based on its damage states. Bridge functionality is quantified by mapping the current damage state to a functionality value between 0 and 1.0. A value of 1.0 is associated with DS_1, indicating no damage. Conversely, 0 denotes that the structure is categorized as DS_5, completely damaged. The expected functionality can be obtained by multiplying the probability of being in each damage state with the corresponding functionality ratio. Consequently, functionality of a bridge under a given seismic hazard can be computed as

$$Func = \sum_{i=1}^{5} FR_i \cdot P_{S=DS_i|IM} \tag{6}$$

where FR_i is the functionality ratio associated with damage state i (i.e., none, slight, moderate, major, and complete).

The resilience performance indicator attempts to quantify recovery patterns of structural systems under hazard effects. In HAZUS99 (ATC 1999), the bridge functionality restoration process is modeled by a normal cumulative distribution function corresponding to each of the four bridge damage states (i.e., slight, moderate, major, and complete). The recovery functions are dependent on their associated damage states (Shinozuka *et al.* 2008). The most widely adopted approach to quantify the resilience of a structural system is to compute it as the integration over time of the functionality under investigation (Cimellaro *et al.* 2010; Frangopol and Bocchini 2011).

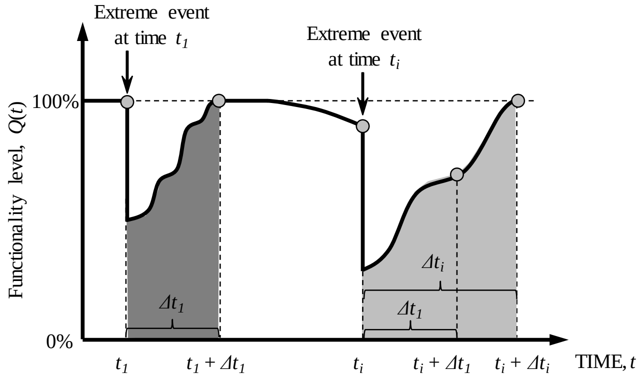

Figure 2. Schematic representation of bridge resilience assessment under seismic hazard considering time effects

$$R_{Resi} = \frac{1}{t_r} \int_{t_0}^{t_0+\Delta t_r} Q(t)dt \tag{7}$$

in which $Q(t)$ is the functionality of a bridge under recovery function at time t (e.g., days and months); t_0 is the occurrence time of the extreme event; and Δt_r is the investigated time interval. The resilience, as computed by Eq. (7), can be illustrated graphically as shown in Figure 2 considering aging effects. As qualitatively shown in this figure, a relatively smaller value of resilience may result when the extreme event occurs at a later stage of the investigated time, given the same investigated time interval (e.g., Δt_1). This figure aims to qualitatively show the aging effects on the resilience assessment of a highway bridge under seismic hazard.

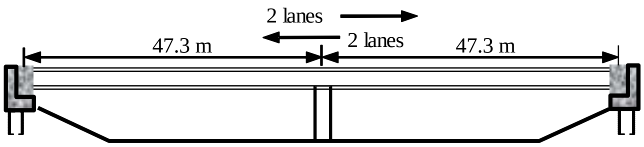

Figure 3. Elevation of the bridge under investigation

5. ILLUSTRATIVE EXAMPLE

The proposed framework is applied to an existing highway bridge located in Coyote, California, USA. The time-variant risk, resilience, and sustainability assessment of this two-span prestressed concrete continuous bridge is investigated throughout its service life. The bridge is located at the intersection of Bailey Ave. and US Highway 101 and was built in

2004. The bridge has two spans of equal length (47.3 m) and carries two lanes of traffic in each direction. The schematic layout of the bridge, with the length of 94.6 m and the width of 19.2 m, is shown in Figure 3. The lifetime is assumed to be 75 years.

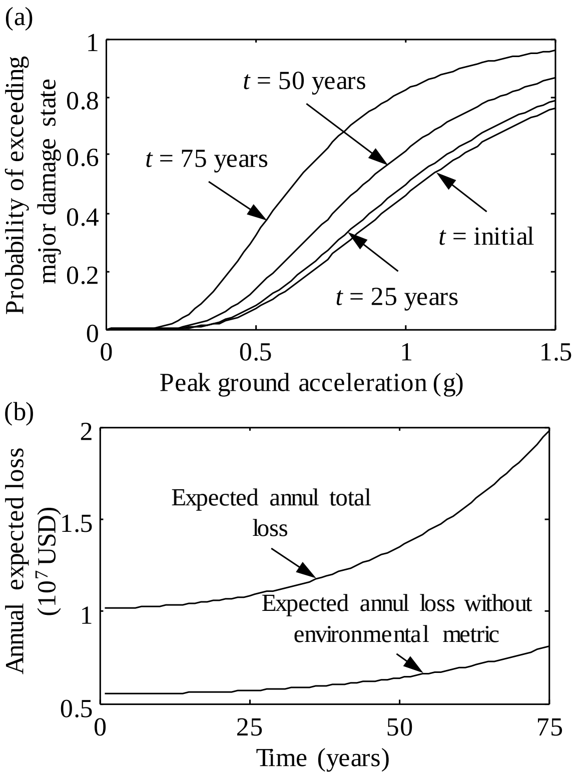

Figure 4. (a) Fragility curves associated with the bridge for major damage state at t = 0, 25, 50, and 75 years and (b) expected annual total seismic loss with and without considering the environmental metric

The moment magnitudes considered in this paper are greater than $M_W \geq 6.0$ and go up to 8.0; these magnitudes characterize the seismic events associated with the San Andreas Fault. The distance between the location of the bridge and the epicenter of a possible earthquake is assumed to be uniformly distributed in order to capture the spatial uncertainties. The probabilistic earthquake scenarios are selected based on the seismic rupture sources in the SFBR. The annual recurrence rate of seismic scenarios, 0.0045/year, is considered based on USGS data (2003). The PGA is used as a measure of the ground motion intensity herein.

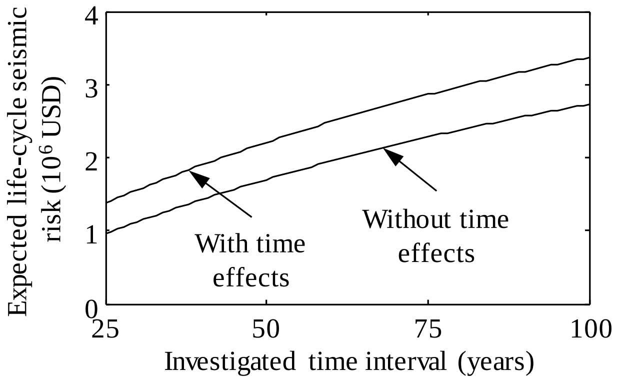

Figure 5. Evaluation of life-cycle seismic risk of the highway bridge with and without aging effects under different time intervals

Over time, structural vulnerability increases due to aging effects. The investigated time horizon is considered to start from the year when the bridge was built and extends 75 years. The initial values of the fragility parameters are based on Basöz and Mander (1999). The parameters of deteriorated fragility curves are assumed to decrease (Decò and Frangopol 2013). The time-variant parameters of the fragility curves can be obtained by using Eq. (1). In order to illustrate the time effects on fragility curves, the seismic fragility curves for the representative bridge are presented in Figure 4(a) for *t* = 0, 25, 50, and 75 years. Each curve in this figure represents the probability of exceeding a major damage state for a given value of PGA. It is evident from Figure 4(a) that the probability of exceeding the major damage state increases with time. The time-variant losses associated with the bridge under seismic hazard are computed using Eq. (4). The expected annual seismic loss is shown in Figure 4(b). There is a significant difference between the two cases (i.e., with and without considering the environmental metric) presented within this figure and the environmental metric contributes significantly to the total seismic loss. Overall, it is of vital importance to consider the time effects within the seismic performance assessment of bridges under seismic hazard.

The life-cycle seismic risk considering time effects can be computed using Eq. (5). The life-cycle seismic risk under different time intervals is shown in Figure 5. There is a significant difference between the cases without and with consideration of time effects. As the time interval increases, this difference increases. Consequently, the time effects should be considered in the life-cycle seismic risk assessment process. In general, discarding aging effects leads to the underestimation of seismic loss.

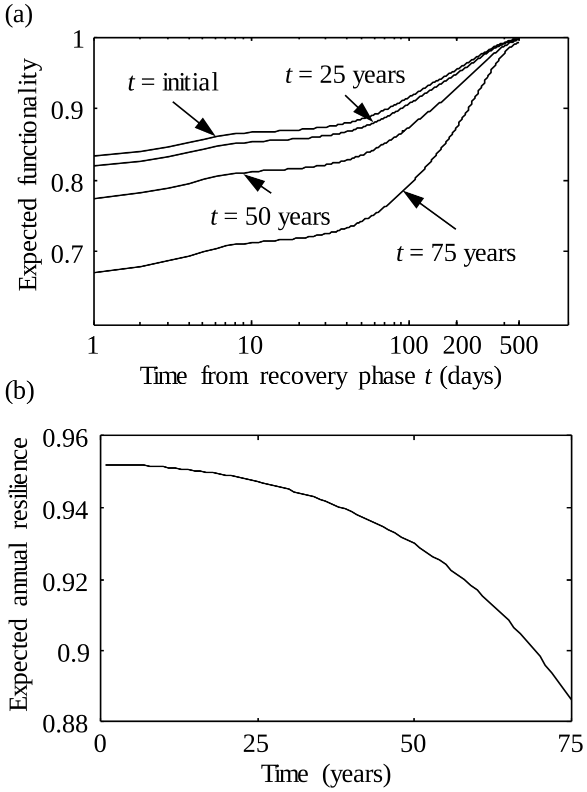

Figure 6. (a) Expected functionality of the bridge from the recovery phase and (b) expected annual resilience of the bridge under seismic hazard

The annual resilience assessment of the investigated highway bridge under seismic hazard is also studied in this paper. The functionality associated with complete damage is 0 while the functionality corresponding to intact state is 1.0. The values of functionality for other damage states are assumed to follow triangular distributions. More detailed information can be found in Dong and Frangopol (2015). By performing recovery strategies, the functionality of a bridge can increase to a desirable level. The probabilistic time-variant functionality of the bridge is computed using Eq. (6) and displayed in Figure 6(a). There is a considerable difference between the cases at different points in time (i.e., t = 0, 25, 50, 75 years). As evidenced from Figure 6, the aging has a major effect on the residual functionality of the bridge under given seismic scenarios. As time goes by, the functionality of the bridge would reach a desirable level after the recovery action. Subsequently, the expected value of the bridge functionality can be used for the computation of the resilience. Using Eq. (7), the resilience of the bridge can be obtained. The expected annual resilience of the bridge under seismic hazard is shown in Figure 6(b). As indicated, the resilience of the bridge decreases with time. Given the risk and resilience thresholds, the optimal design and seismic mitigation strategy can be obtained.

6. CONCLUSIONS

This paper presents a methodology for the risk, resilience, and sustainability assessment of highway bridges under seismic hazard in a life-cycle context considering uncertainties. The time effects have great impact on these three metrics. The difference between the life-cycle seismic risk with and without aging effects increases as the investigated time interval increases. Additionally, the expected seismic risk depends heavily on the environmental metric. Therefore, the parameters associated with this metric should be carefully quantified. Moreover, due to aging effects, the resilience of damaged structures under seismic hazard decreases significantly with time. Within the context of performance-based engineering, risk, resilience, and sustainability metrics provide decision makers additional information necessary for realistic assessment of structural systems after disasters caused by extreme events. Ultimately, the information obtained considering these metrics can be used in design, maintenance, and retrofit optimization processes of infrastructure systems under extreme events.

ACKNOWLEDGEMENTS

The support from the U.S. Federal Highway Administration Cooperative Agreement Award DTFH61-07-H-00040 is gratefully acknowledged. The constructive comments provided by Samantha Sabatino (Ph. D candidate at Lehigh University) are also gratefully acknowledged. The opinions and conclusions presented in this paper are those of the authors and do not necessarily reflect the views of the sponsoring organization.

7. REFERENCES

Adams, W.M. (2006). "The future of sustainability: Re-thinking environment and development in the twenty-first century," *Report of the IUCN Renowned Thinkers Meeting*, (http://cmsdata.iucn.org/downloads/iucn_future_of_sustanability.pdf).

ATC (1999). "Earthquake damage evaluation data for California," *Technical Report ATC-13,* Applied Technology Council.

Barone, G. and Frangopol, D.M. (2014). "Life-cycle maintenance of deteriorating structures by multi-objective optimization involving reliability, risk, availability, hazard and cost," *Structural Safety*, 48, 40-50

Basöz, N., and Mander, J. (1999). "Enhancement of the highway transportation lifeline module in HAZUS," *National Institute of Building Sciences* (NIBS), Washington, D.C., United States.

Bocchini, P., Frangopol, D.M., Ummenhofer, T., and Zinke, T. (2014). "Resilience and sustainability of the civil infrastructure: Towards a unified approach," *Journal of Infrastructure Systems*, 20(2), 04014004, 1-16.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., and Winterfeldt, D.V. (2003). "A framework to quantitatively assess and enhance the seismic resilience of communities," *Earthquake Spectra*, 19, 733-752

Campbell, K.W., and Bozorgnia, Y. (2007). "Campbell-Bozorgnia NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion Parameters," *PEER Report 2007/02, Pacific Earthquake Engineering Research Center*, University of California, Berkeley, CA, United States.

Cimellaro, G.P., Reinhorn, A.M., and Bruneau, M. (2010) "Seismic resilience of a hospital system," *Structure and Infrastructure Engineering*, 6, 127–144.

Decò, A., and Frangopol, D.M. (2013). "Life-cycle risk assessment of spatially distributed aging bridges under seismic and traffic hazards," *Earthquake Spectra*, 29(1): 127-153.

Dong, Y., Frangopol, D.M., and Saydam, D. (2013). "Time-variant sustainability assessment of seismically vulnerable bridges subjected to multiple hazards," *Earthquake Engineering and Structural Dynamics*, 42(10), 1451-1467.

Dong, Y., Frangopol, D.M., and Saydam, D. (2014). "Pre-earthquake probabilistic retrofit optimization of bridge networks based on sustainability," *Journal of Bridge Engineering*, 19(6), 04014018, 1-10

Dong, Y., and Frangopol, D.M. (2015). "Risk and resilience assessment of bridges under mainshock and aftershocks incorporating uncertainties," *Engineering Structures*, 83, 198-208.

Ellingwood, B.R. (2005). "Risk-informed condition assessment of civil infrastructure: State of practice and research issues," *Structure and Infrastructure Engineering*, 1(1), 7-18.

Frangopol, D.M. (2011). "Life-cycle performance, management, and optimization of structural systems under uncertainty: accomplishments and challenges," *Structure and Infrastructure Engineering*, 7(6), 389-413.

Frangopol, D.M., and Bocchini, P. (2011). "Resilience as optimization criterion for the rehabilitation of bridges belonging to a transportation network subjected to earthquake," *In: SEI-ASCE 2011 Structures Congress.* April 14-16, 2011, Las Vegas, NV.

Mander, J.B. (1999). "Fragility curve development for assessing the seismic vulnerability of highway bridges," *Technical Report*, University at Buffalo, State University of New York, NY, United States.

MathWorks (2013). The MathWorks, Inc., Natick, MA.

Saydam, D., Frangopol, D.M., and Dong, Y. (2013). "Assessment of risk using bridge element condition ratings," *Journal of Infrastructure Systems*, 19(3), 252-265.

Shinozuka, M., Zhou, Y., Kim, S.H., Murachi, Y., Banerjee, S., Cho, S., and Chung, H. (2008). "Social-economic effect of seismic retrofit implemented on bridges in Los Angeles highway network," *Report No. CA06-0145*, Department of Civil and Environmental Engineering, University of California, Irvine, California.

United States Geological Survey (USGS) (2003). "Earthquake probabilities in the San Francisco Bay Region: 2002–2031," *Open File Report 03-214*, Menlo Park, California.

Yeo, G.L., and Cornell, C.A. (2005). "Stochastic characterization and decision bases under time-dependent aftershock risk in performance-based earthquake engineering," *PEER Report 2005/13*, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.