Use of Seismic Risk Analysis of Roadway Systems to Facilitate Performance-Based Engineering and Risk-Reduction Decision Making

by

Stuart D. Werner[1], Sungbin Cho[2], Craig E. Taylor[3], and Jean-Paul Lavoie[4]

ABSTRACT

A new methodology for seismic risk analysis (SRA) of roadway systems has been programmed into a software package named REDARS™ 2. This paper describes this methodology, along with results from its application to a roadway system in the Los Angeles area. This application shows how SRA results can support performance-based engineering, assessment of system resilience, and seismic-risk reduction decision making.

INTRODUCTION

Experience has shown that earthquake damage to highway components (bridges, roadways, tunnels, etc.) can lead to life-safety risks and damage-repair costs. However, this is but one consequence of this damage. In addition, such damage can disrupt traffic flows and this, in turn, can impact the region's economy and its emergency response and recovery. Furthermore, the extent of these impacts will not only depend on the seismic response of the individual components, but also on the characteristics of roadway system that contains these components. System characteristics that will affect post-earthquake traffic flows include: (a) the network configuration; (b) locations, redundancies, and traffic-carrying capacities of the system's roadway links; and (c) locations of the components within these links (Basoz and Kiremidjian, 1996; Wakabashi, 1999; Shinozuka et al.., 2004; Werner et al., 2006).

Thus, it is evident that life-safety protection is not the sole requirement for the successful design of a roadway system against earthquakes. Rather, acceptable performance and resilience of the system must also be achieved in order to ensure rapid recovery and minimal impact on the socio-economic fabric of the surrounding region. This, in turn, leads to the concept of performance-based engineering of the roadway system which, in addition to the seismic performance of the individual components, must consider the system's ability to accommodate the affected region's traffic demands as soon as possible after the earthquake.

Essential to the assessment of a roadway system's resilience and seismic performance is the availability of technically-sound methodologies for seismic risk analysis (SRA) of an overall roadway system. In recognition of this need, the Federal Highway Administration (FHWA) has, since 1993, been researching SRA methodologies under its multiyear seismic-research program. The culmination of this research has been the development of a new

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[1] President, Seismic Systems & Engineering Consultants, Oakland CA
[2] Project Engineer, ImageCat Inc., Long Beach CA
[3] President, Natural Hazards Management Inc., Torrance CA
[4] Principal, Geodesy, San Francisco CA

methodology named REDARS™ (Risks from Earthquake DAmage to the Roadway System). This methodology has been programmed into a software package (REDARS™ 2) that has been applied to roadway systems in the San Francisco Bay area and in Los Angeles and, more recently, to systems in Oregon, Utah, and Southern California as well.

This paper summarizes the REDARS™ methodology along with a demonstration application of the methodology to a Los Angeles area roadway system. This application illustrates how SRA results can be used to assess a roadway system's seismic performance and resilience, and to support seismic-risk-reduction decision making.

SRA METHODOLOGY

The REDARS™ SRA methodology is shown in Figure 1. It includes input-data development and analysis setup (Step 1), seismic analysis of the roadway system for multiple simulations, (Steps 2 and 3), and aggregation of the results from each simulation (Step 4). In this, a simulation is defined as a complete set of system SRA results for one set of uncertain input and model parameters. The numerical values of these parameters may differ from one simulation to another because of random and systematic uncertainties.

The heart of this methodology is a series of modules that contain the input data and models needed to characterize: (a) the roadway system and its post-earthquake travel times, traffic flows, and trip demands (system module); (b) the seismic hazards (hazards module); (c) the component damage states, how this damage will be repaired, and the component's resulting traffic states (i.e., whether it will be partially or fully closed to traffic during the repairs) at various times after the earthquake (component module); and (d) the economic losses due to repair costs and travel disruption (economic module) (Fig. 2). This modular structure will facilitate the inclusion of new improvements to the REDARS™ 2 hazards, component, and network models as they are developed from future research.

REDARS™ 2 uses a walkthrough process that considers earthquake occurrences over a specified time duration (typically thousands of years). For each year of the walkthrough, random samplings of a regional earthquake model are used to establish the number of earthquakes occurring during that year, and each earthquake's magnitude and location. These results are stored in a "walkthrough table" which contains a year-by-year tabulation of these earthquake occurrences. Then, the following SRA steps are carried out to develop a simulation for each earthquake occurrence during each year of the walkthrough:

- ***Uncertain Parameters.*** Values of all uncertain parameters are randomly selected.
- ***Seismic Hazards.*** Seismic hazard models from the Hazards Module are used to estimate site-specific ground-shaking and ground-deformation hazards at each component's site.
- ***Component Performance.*** Fragility models from the Component Module are used to estimate each component's damage state due to these hazards, and its repair cost, downtime, and traffic state at various post-earthquake times as the repairs proceed. The component traffic states are used to develop post-earthquake "system states" (roadway closures throughout the system at various post-earthquake times).

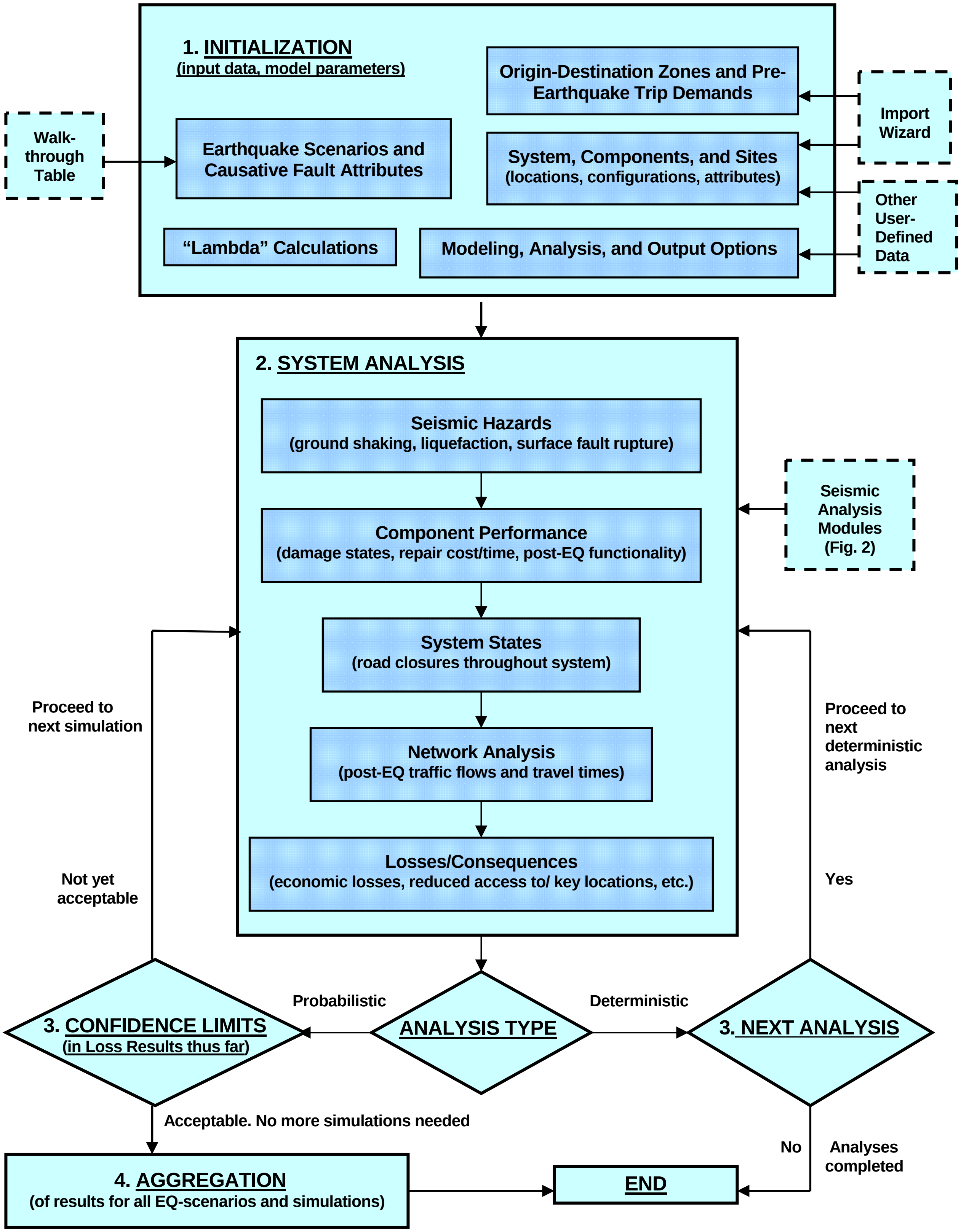


Figure 1. REDARS$^{™}$ Methodology for SRA of Roadway Systems

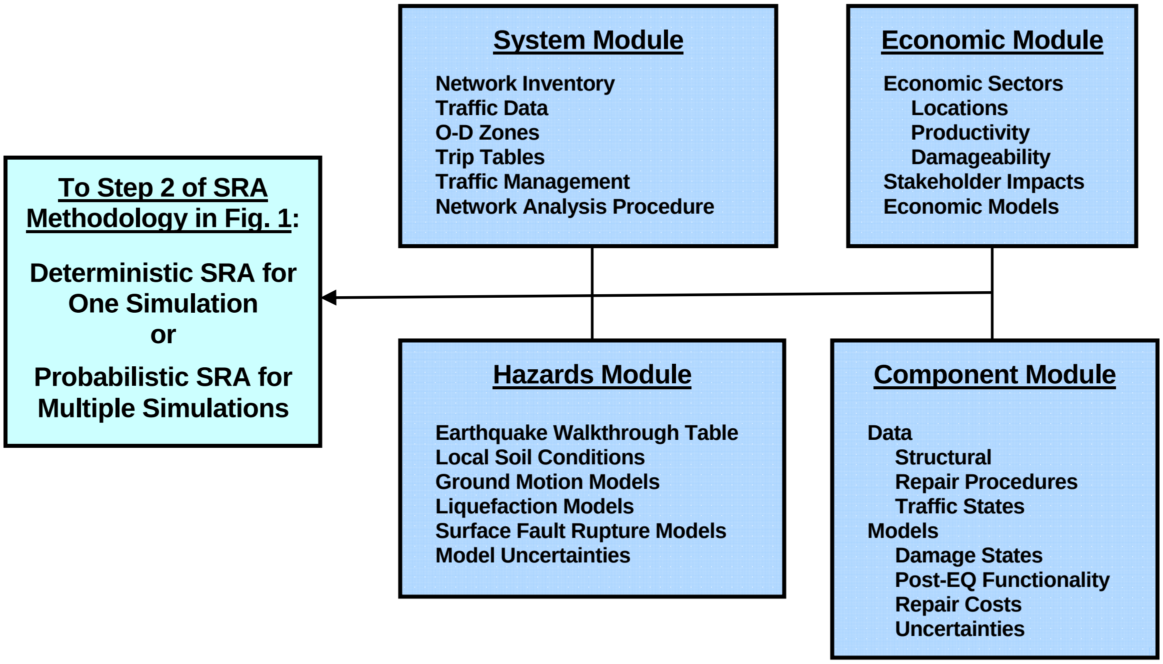


Figure 2. REDARS™ Seismic Risk Analysis Modules

- ***Network Analysis.*** The network analysis procedure in the System Module is applied to each system state at each post-earthquake times, to estimate travel times, traffic flows, and trip demands.
- ***Loss Estimation.*** The above results are used to estimate various types of losses due to earthquake damage to the roadway system, such as economic losses, increased travel times to/from key locations and along key routes, and reduced trip demands.

After each simulation is completed, a variance-reduction statistical-analysis procedure computes and displays confidence intervals (CIs) in the average annual economic-loss results. At any time, the user can stop the SRA to examine these CIs and other results obtained thus far. If the CIs are deemed acceptable, the SRA can be ended; otherwise, the SRA can be restarted and continued in order to develop additional simulations (Fig. 1).

DEMONSTRATION APPLICATION

This section summarizes an application of REDARS™ 2 to a roadway system in Los Angeles California (termed the LA-testbed system), to demonstrate the types of SRA results that can be obtained and how they can support seismic-risk-reduction decision making.

Input Data and Analysis Procedures

Roadway System

Figure 3 shows the LA-testbed roadway system that has been analyzed. This system extends from the town of Santa Clarita to the north to beyond the Century Freeway (I-105) to the south, and from the Pacific coast east to just beyond downtown LA. It is this region of the greater LA area that was most affected by the 1994 Northridge Earthquake. Within this region, 10 bridges collapsed during this earthquake, and several other bridges were extensively damaged.

The REDARS™ 2 model of this system (Fig. 4) includes the system's freeways and major arterials. It contains 1,694 nodes and 5,100 links, whose locations and traffic capacities are obtained from the Highway Performance Monitoring System (HPMS) and the National Highway Planning Network (NHPN), as accessed and processed by the REDARS™ 2 Import Wizard (Cho et al., 2006).

Source:http://maps.google.com

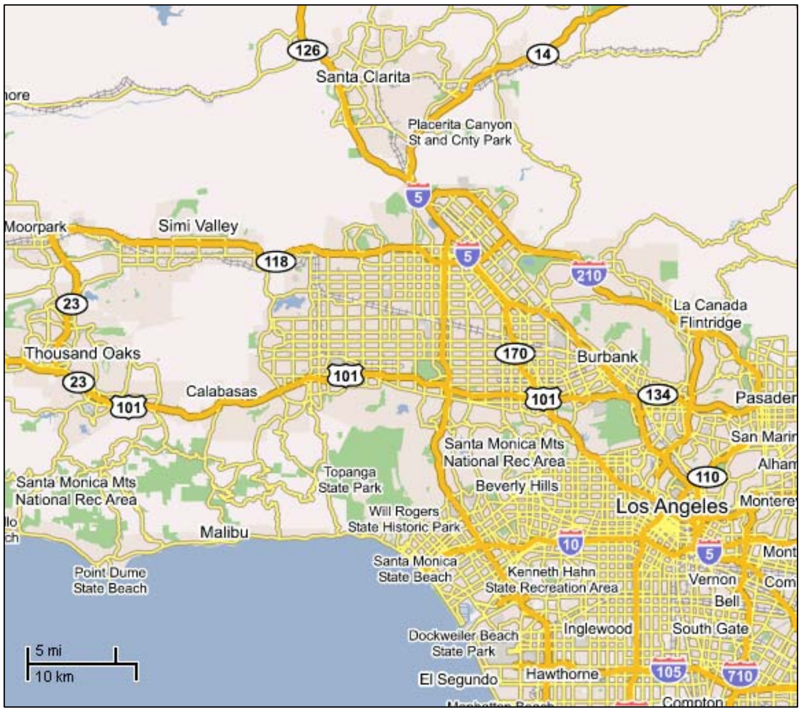


Figure 3. LA-Testbed Roadway System

Components

This LA-testbed roadway system contains 944 bridges, 1,709 approach fills and 5 tunnels. The attributes of the various bridges are based on data from the National Bridge Inventory (NBI) database, as accessed and processed by the REDARS™ 2 Import Wizard. At the time of the 1994 Northridge Earthquake, 57 of the 944 bridges in this system had been retrofitted by column jacketing. After that earthquake, and through the end of 2004, an additional 231 were column jacketed -- resulting in a total of 288 column-jacketed bridges as of that time (Yashinsky, 2005). Figure 5 shows the locations of the column-jacketed bridges throughout the LA-testbed system before and after these additional 231 retrofits were completed. The structural capacities of these column-jacketed bridges were estimated by applying retrofit enhancement factors described in Shinozuka (2004).

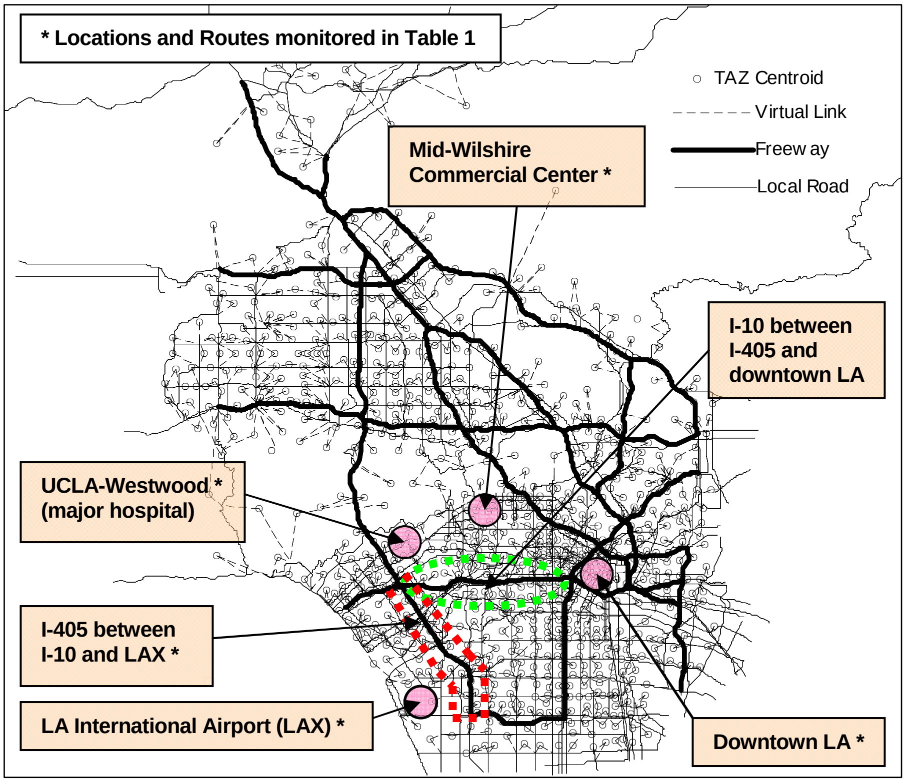
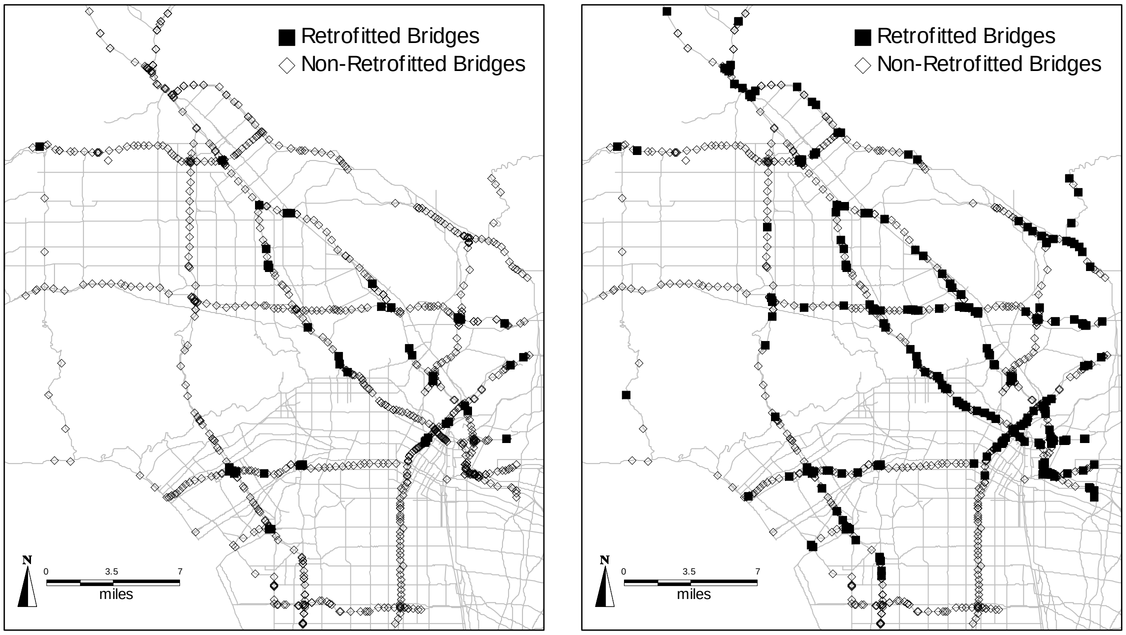


Figure 4. REDARS™ 2 Model of LA-Testbed Roadway System



a) Pre-Northridge-Earthquake System (early 1994)

b) System as of End of 2004

Figure 5. Column-Jacketed Bridges in LA-Testbed Roadway System

Soil Conditions

The soils along the roadways in this system consist of soft rock and firm soils, which are represented in REDARS$^{\text{TM}}$ 2 primarily as NEHRP site classifications C and D. None of the soils within the system are considered to be prone to liquefaction hazards.

Traffic Analysis Zones

The area around this LA-testbed roadway system was modeled using 977 traffic-analysis zones (TAZs) whose locations and trips to all other zones are based on data from the Southern California Area of Governments (SCAG). Figure 2 shows the centroids of these TAZs. In addition, 59 external TAZs were included in order to represent aggregations of trips into and out of the region from locations beyond the region. In this REDARS$^{\text{TM}}$ 2 model, 3,908 virtual links were used to connect the centroid of each TAZ to the actual highway-roadway system. Figure 4 shows those particular TAZs for which earthquake effects on travel to-and-from the zones are displayed in this paper. Werner et al. (2006) also provides such results for several other TAZs.

Routes

Figure 4 shows routes in the LA-testbed system whose post-earthquake travel times have been monitored. Travel-time delays along these routes are displayed later in this paper.

Earthquake Walkthrough Table

Under this project, a walkthrough file that defines earthquake occurrences over a 10,000-year duration was developed for all of coastal California. This file was developed from application of earthquake models developed at the United States Geological Survey (USGS) (Frankel et al., 2002), along with new data from the California Geological Survey, the Northern California Earthquake Data Center, and the Southern California Earthquake Center). The walkthrough file used for this SRA of the LA-testbed roadway system contains earthquakes from the coastal California file that are located within about 200 miles of this system. This file includes 7,035 earthquakes with a moment magnitude (M_w) ≥ 5.0. Of these, our calculations show that 2,645 of these events actually damaged the testbed system. Werner et al. (2006) provides further detail on this walkthrough file.

Seismic Hazard and Component Models

This SRA considered ground-shaking and fault-rupture hazards to bridge, pavement, tunnel, and approach-fill components. These hazards and component vulnerabilities were modeled as follows: (a) ground motion hazards were estimated by the Abrahamson-Silva, (1997) model; (b) fault rupture hazards were estimated by an adaptation of the Youngs et al. (2003) model; (c) bridge damage due to ground shaking was estimated from a version of the HAZUS99-SR2 model (FEMA, 2002) that was modified under this project to improve comparisons between its bridge-damage predictions and the observed damage from the Northridge Earthquake; (d) retrofit-enhancement factors developed by Shinozuka (2004) were used to represent effects of column jacketing in the above bridge-damage model; (c) HAZUS99-SR2 models were used to estimate bridge damage from ground displacement and tunnel damage from ground shaking and ground displacement; and (d) approach-fill and pavement damage models as well as repair models for bridges, approach fills, pavements, and tunnels were estimated from collaboration with senior Caltrans staff.

Results

This demonstration application of REDARS™ 2 to this LA-testbed system has provided a range of analysis results in tabular and graphical form, and also as GIS displays (Werner et al., 2006). This paper discusses two of these sets of results that illustrate: (a) system-performance and resilience measures that can be estimated from probabilistic SRA and how they can be used to assess various seismic-risk-reduction options; and (b) an application of probabilistic SRA to assess the economic viability of an actual bridge-retrofit program that was carried out within the LA-testbed system after the Northridge earthquake.

System Performance and Resilience

Performance Measures

As noted earlier, REDARS™ 2 can provide tabulations and GIS-displays of a variety of deterministic or probabilistic representations of earthquake-induced losses, such as (a) economic losses; (b) increased travel times and/or reduced trip demands to/from any location, and (c) increased travel times along any route. Table 1 provides probabilistic estimates of such results for the particular locations and routes shown in Figure 4.

All of these results are measures of the seismic performance of the LA-testbed roadway system, and all depend not only on the performance of the various components in the system, but also on the layout, redundancies, and traffic-carrying capacities of the roadways in the system. These performance measures represent an improved basis for seismic-risk-reduction decision making, since they show how various risk-reduction options can affect post-earthquake traffic flows and travel times. For example, such measures can show how these traffic flows and travel times are affected by: (a) alternative bridge retrofit priorities; (b) alternative seismic design or retrofit levels; (c) alternative post-earthquake repair strategies, such as the bonus-incentive program that Caltrans implemented after the Northridge Earthquake in order to replace collapsed bridges along major freeways; and (d) alternative traffic-management strategies (Buckle, 2003; Werner et al., 2006).

System Resilience

The above types of results can also be used to characterize the roadway system's performance in terms of its post-earthquake resilience, which can be defined as the ability of the system to recover rapidly from an earthquake event (NSF, 2007). Just how to characterize resilience of a roadway system in terms of these results is expected to be an area of active research in the near future. However, for purposes of discussion within this paper, one possible way to represent roadway-system resilience is summarized below.

Table 1. Probabilistic Estimates of Losses from SRA of LA-Testbed Roadway System

Loss	Location or Route (see Fig. 2)	Time after Earthquake	Loss Value at Various Probabilities of Exceedance over 50-Year Exposure Time, percent			
			Probability of Exeeedance =			
			5-percent	10-percent	20-percent	50-percent
Economic Loss	--	--	$1,245M	$1,082M	$935M	$690M
Increase in Access Times to Key Locations. percent (relative to pre-EQ time)	To LA International. Airport (LAX)	7 Days	27.6%	23.5%	19.5%	12.2%
		60 Days	17.4%	14.2%	7.5%	2.9%
	To UCLA-Westwood (which contains a major hospital)	7 Days	14.7%	13.3%	12.0%	6.1%
		60 Days	9.3%	7.1%	5.9%	3.1%
Reduction in Trip Attraction to Key Locations, percent (relative to pre-EQ trips)	To Downtown LA	7 Days	17.4%	16.1%	14.3%	8.0%
		60 Days	9.4%	6.5%	4.8%	2.2%
	To Mid-Wilshire Commercial Center.	7 Days	11.8%	8.7%	5.8%	3.3%
		60 Days	4.1%	3.0%	2.2%	1.3%
Increases in Travel Times along Key Routes, percent (relative to pre-EQ times)	Along I-10, from I-405 to Downtown LA	7 Days	276.3%	253.8%	227.2&	165.1%
		60 Days	178.5%	157.1%	128.4%	49.1%
	Along I-405, from I-10 Interchange to LAX	7 Days	161.4%	139.8%	121.5%	69.1%
		60 Days	85.4%	71.6%	52.3%	6.4%

Let us define a “post-earthquake resilience time” as the time after the earthquake that would be required for the system-wide travel times to attain their pre-earthquake levels (or some acceptable fraction of these pre-earthquake levels). For a given system, this resilience time will vary over the range of earthquake events that could occur within the surrounding region. Representation of these earthquakes will need to consider uncertainties in earthquake magnitude, location, and occurrence rate, in accordance with accepted regional earthquake models. To account for these uncertainties, as well as uncertainties in the estimation of seismic hazards and component damage states, one can use REDARS™ to perform a probabilistic SRA that computes resilience time as a function of return period (or probability of exceedance over various exposure times). From this, whether a roadway system is acceptably resilient can be defined in terms of whether the resilience times at certain designated return periods are acceptably short. Just what constitutes an “acceptable” resilience time should be determined by balancing the costs that would be required to upgrade the system to achieve a given resilience time against the socio-economic impacts to society that would result if this level of resilience is not achieved.

A roadway system's resilience time for a given earthquake will depend on such factors as: (a) the seismic performance characteristics of the individual components within the system, which will depend on their seismic design/retrofit, geometry, age, and current condition; (b) the rate at which damage to the components can be repaired, which will depend on the available repair resources and how rapidly these resources can be mobilized at the sites of the damaged components; (c) the roadway links along which the damaged components are located; and (d) the redundancy and traffic carrying capacity of the roadway links; and (d) the trip demands on these system which will vary according to the post-earthquake traffic carrying capacity of the system's roadway links. All of these factors are considered in the REDARS™ SRA methodology, thereby enabling it readily estimate resilience times, The methodology can also be used to carry out sensitivity analyses to: (a) better understand the relative importance of the above factors to the estimation of these resiliency times; and (b) explore the relative effects of various seismic-risk-reduction options on the roadway system's resiliency time (e.g., alternative bridge retrofit priorities, post-earthquake bridge repair options, post-earthquake traffic management options, etc.).

Regardless of how roadway-system resilience is actually characterized, the above factors will all affect the estimation of the system's post-earthquake resilience. Thus, as the importance of characterizing post-earthquake roadway-system resilience becomes more widely recognized, the motivation to further develop and enhance REDARS™ and other roadway-system SRA methodologies that can directly account for the above factors should continue to increase.

Assessment of Economic Viability of Bridge Retrofits in LA-Testbed System

Probabilistic SRA results from this demonstration application were used to assess a bridge retrofit program that was actually implemented by Caltrans within the LA-testbed roadway system. This program involved the column jacketing of 231 bridges over a time period that extended from 1994 (after the Northridge Earthquake) through the end of 2004. This application further demonstrates the possible use of system-performance requirements in seismic-risk-reduction decision making, by illustrating how roadway-system SRA results can be used to evaluate the economic viability of a bridge-retrofit program.

Suppositions

Just before the 1994 Northridge Earthquake, only 57 of the bridges in the testbed system had been column-jacketed (see Fig. 5a). Then, after this earthquake, suppose Caltrans is considering a program to column-jacket an additional 231 bridges in the LA-testbed system (see Fig. 5b). Finally, suppose that their decision as to whether to proceed with this program will depend on the results of an analysis of the program's economic viability, which will evaluate the extent to which these 231 bridge retrofits might reduce the economic losses due to earthquake-induced damage and traffic disruption. The following paragraphs describe how a REDARS™ 2 probabilistic SRA can be used to carry out such an economic analysis.

Analysis Approach

This analysis involves: (a) estimation of the costs to carry out the column-jacketing retrofit of these 231 bridges; (b) estimation of the average economic loss due to earthquake damage to the testbed roadway system, with and without the 231 bridge retrofits; and (c) estimation of the standard deviation of these losses, also with and without the 231 retrofits.

Estimation of Retrofit Costs. The retrofit costs were estimated from data provided by Caltrans (Bailey, 2005). These data show that the Caltrans bridge–retrofit program throughout the greater LA area included the column jacketing of 625 bridges, at a total cost of about $300,000,000. This results in an average retrofit cost per bridge of $300,000,000/625 = $480,000. Using this average, the cost to retrofit the 231 bridges in this testbed system was estimated to be $480,000 x 231 = $110,880,000 $\approx$ $111,000,000.

Computation Steps to Estimate Retrofit Benefits. In this step, the present value of the economic losses for appropriate exposure times and discount rates was calculated (where the discount rate is defined as the difference between the rate charged to borrow money and the inflation rate). This calculation consisted of the following steps:

- REDARS™ 2 was used to perform a probabilistic SRA of the LA-testbed system as of early 1994, before any of the 231 bridge retrofits were in place (Fig. 5a). The results of this SRA were used to compute the average annualized losses (AAL_{1994}) and the standard deviation of the losses (σ_{1994}). This AAL included repair costs along with losses from travel-time delays and trips foregone due to earthquake damage to the roadway system.
- REDARS™ 2 was then used to perform a probabilistic SRA of the LA-testbed system as of late 2004, when all of the 231 bridge retrofits were in place (Fig. 5b). The results of this SRA were used to compute the AAL (as defined above) and the standard deviation of the losses (AAL_{2004} and σ_{2004}.respectively).
- The difference between the above *AALs* for the LA-testbed roadway system before and after the 231 bridge retrofits was computed to be $\Delta_{AAL} = AAL_{1994} - AAL_{2004}$. Then, Equation 1 was used to compute the present value of this loss difference (PVL) for each of the above exposure times T and discount rates j. This value of PVL represented the assumed benefit of the retrofit of these 231 bridges. In this example, PVL is computed for a range of plausible exposure times and discount rates.

$$PVL = \left[\frac{1-(1+j)^{-T}}{j} \right] * \Delta_{AAL} \tag{1}$$

Basis for Assessing Economic Viability of this Bridge Retrofit Strategy. The process for assessing the economic viability of the strategy to retrofit 231 bridges interprets this strategy in terms of a possible investment in seismic-risk reduction. To evaluate the soundness of this investment, its potential for a good financial yield should, of course, be considered. In addition, a prudent investment should not be overly risky or volatile. The financial yield and volatility of this investment have been assessed as described below:

- The potential financial yield of this bridge retrofit investment has been represented in terms of the ratio of the potential benefits of the investment (assumed here to correspond to the parameter *PVL* as computed above) to the cost of the investment (which corresponds to the estimated retrofit cost of $111,000,000). That is, a high benefit/cost ratio would represent a very good yield on investment.
- The potential volatility of this investment in the 231 bridge retrofits has been represented by the standard deviation of the losses over this 10,000-year walkthrough period. That is, a significant reduction in the standard deviation of the losses after the 231 bridge retrofits are in place, relative to the standard deviation of the losses prior to the retrofits, would indicate that the investment is favorable from a reduced-volatility standpoint.
- The exposure times that were used in this analysis were based on the estimated design life of a California bridge, which Caltrans has assumed to be about 75 years (Yashinsky, 2005). To bracket this estimate, exposure times of 50 years, 75 years, and 100 years were used. In addition, discount rates of 2.5%, 4%, and 7% were considered, in order to represent a range of discount rates that have been used over the past several years.

Analysis Results

Benefit-Cost Ratios. The benefit-cost ratios for the above-indicated exposure times and discount rates are shown in Table 2. For these various exposure times, the results show benefit-cost ratios that range from about 2.4 for the discount rate of 7%, to about 3.2 to 4.7 when the discount rates of 2.5% and 4% are used. These results suggest that the retrofit of these 231 bridges would represent a cost-effective investment in seismic risk reduction.

Table 2. Benefit-Cost Ratios for Caltrans' Retrofit of 231 Bridges in LA-Testbed Roadway System between 1994 and 2004

Exposure Time	50 Years			75 Years			100 Years		
Discount Rate	2.5%	4%	7%	2.5%	4%	7%	2.5%	4%	7%
Benefit-Cost Ratio	3.90	3.19	2.41	4.45	3.42	2.45	4.74	3.51	2.46

Standard Deviation of Losses. Table 3 compares the standard deviations of the losses for the LA-testbed system with and without the 231 bridge retrofits that occurred between 1994 and 2004. The table shows that these retrofits reduce the standard deviation by about 38%. This suggests that the riskiness/volatility of the seismic performance of the LA-testbed roadway system is substantially reduced when the 231 bridge retrofits are in place.

Discussion of Results

The above types of economic-viability results can enable decision-makers to compare how various seismic-risk-reduction options may reduce potential losses due to earthquake damage to a roadway system. Such results, when considered together with other pertinent decision factors (e.g., life safety, various legal and political constraints, etc.) can enable these decision-makers to make a more informed selection of a preferred seismic-risk-reduction option than has been possible in the past.

Table 3. Standard Deviation of Losses prior to and after Caltrans' Retrofit 231 Bridges in LA-Testbed Roadway System between 1994 and 2004

LA-Testbed System	Standard Deviation of Losses	Ratio of Standard Deviation of 2004 System to that of 1994 System
As of early 1994 (prior to additional 231 bridge retrofits)	$218,634,766	0.616
As of end if 2004 (after completing additional 231 bridge retrofits)	$134,718,179	

CLOSING COMMENTS

REDARS™ is a technically advanced process for SRA of roadway systems nationwide. It can be used for pre-earthquake planning (e.g., evaluation of the effects of various seismic-risk-reduction options on roadway-system performance and resilience) and also for post-earthquake evaluations in real time after an actual earthquake (in order to facilitate emergency response). In addition, REDARS™ can develop many different types and forms of SRA results, in order to meet the needs of a wide range of possible users.

Much has been accomplished over the years to bring REDARS™ to its present level of development. However, for REDARS™ to be a viable SRA tool in the future, the continued development of upgrades and improvements to its software and its engineering/scientific models (as per recommendations in Werner et al., 2006) must be an ongoing process. Vital to this development will be the future application of this software by transportation departments and consultants nationwide, and the feedback that they provide.

ACKNOWLEDGEMENTS

This work was sponsored by the FHWA as part of their multi-year seismic research project at the Multidisciplinary Center for Earthquake Engineering Research. Support was also provided by Caltrans under their multi-year REDARS™ Demonstration Project.

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