

# Fragility Based Rehabilitation Decision Analysis

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## Summary

*A method is presented for assessing the seismic performance of structural/nonstructural systems and developing rational strategies for increasing the seismic resilience of these systems. The seismic performance is measured by fragility surfaces, that is, the probability of system failure as a function of moment magnitude and site-to-source distance, consequences of system damage and failure, and system recovery time following seismic events. The input to the analysis consists of (i) seismic hazard, (ii) structural/nonstructural systems properties, (iii) performance criteria, (iv) rehabilitation strategies, and (v) a reference time. Estimates of losses and recovery times can be derived using fragility information, financial models, and available resources. A structural/nonstructural system located in New York City is used to demonstrate the methodology. Fragilities are obtained for structural/nonstructural components and systems for several limit states. Also, statistics are obtained for life time losses and recovery times corresponding to different rehabilitation alternatives.*

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## Introduction

Capital allocation decisions for a health care facility include, for example, opening a new unit, extending or closing some existing units, buying new equipment, and relocating the hospital building. These decisions are based on life cycle capacity, viewed as the level of performance defined for a service, and cost estimates. Existing geotechnical, structural/nonstructural systems can be left as they are or can be retrofitted using one of the available rehabilitation alternatives. Leaving a system as it is seems to be reasonable for short-term decisions but retrofitting the system, despite its initial costs, might be beneficial in the long run. A probabilistic methodology is required to make a rehabilitation decision since seismic hazard and system performance are uncertain. Most of the existing earthquake loss estimation methodologies usually calculate losses including direct and indirect economic and social losses for a given region, based on the maximum credible earthquake. The ATC-13 (ATC, 1985) methodology provides damage and loss estimates, based on expert-opinion, for industrial, commercial, residential, utility and transportation facilities. HAZUS (FEMA, 1999) estimates potential losses on a regional basis and these estimates are essential to decision-making at all levels of government, providing a basis for developing mitigation policy, and response and recovery planning. Both methods were developed to estimate losses for a large number of facilities in a specified region using the maximum credible earthquake and should not be applied to an individual facility. Losses estimated by using the maximum credible earthquake may not be accurate (Kafali and Grigoriu, 2004a).

The main objective of this paper is the development of a methodology for evaluating the seismic performance and development of optimal rehabilitation strategies of individual health care facilities

during a specified time interval. The seismic performance is measured by fragility surfaces, that is, the probability of system failure as a function of moment magnitude and site-to-source distance, consequences of system damage and failure, and system recovery time following seismic events. Estimates of losses and recovery times, referred to as life cycle losses and recovery times, can be derived using fragility information, financial models, and available resources. A health care facility located in New York City is used to demonstrate the methodology. Fragilities and statistics for lifetime losses are obtained for this structural system and some of its nonstructural components.

### Proposed Loss Estimation Method

The proposed loss estimation method is based on (i) seismic hazard analysis, (ii) fragility analysis and (iii) capacity/cost estimation. Figure 1 shows a chart summarizing the loss estimation methodology.

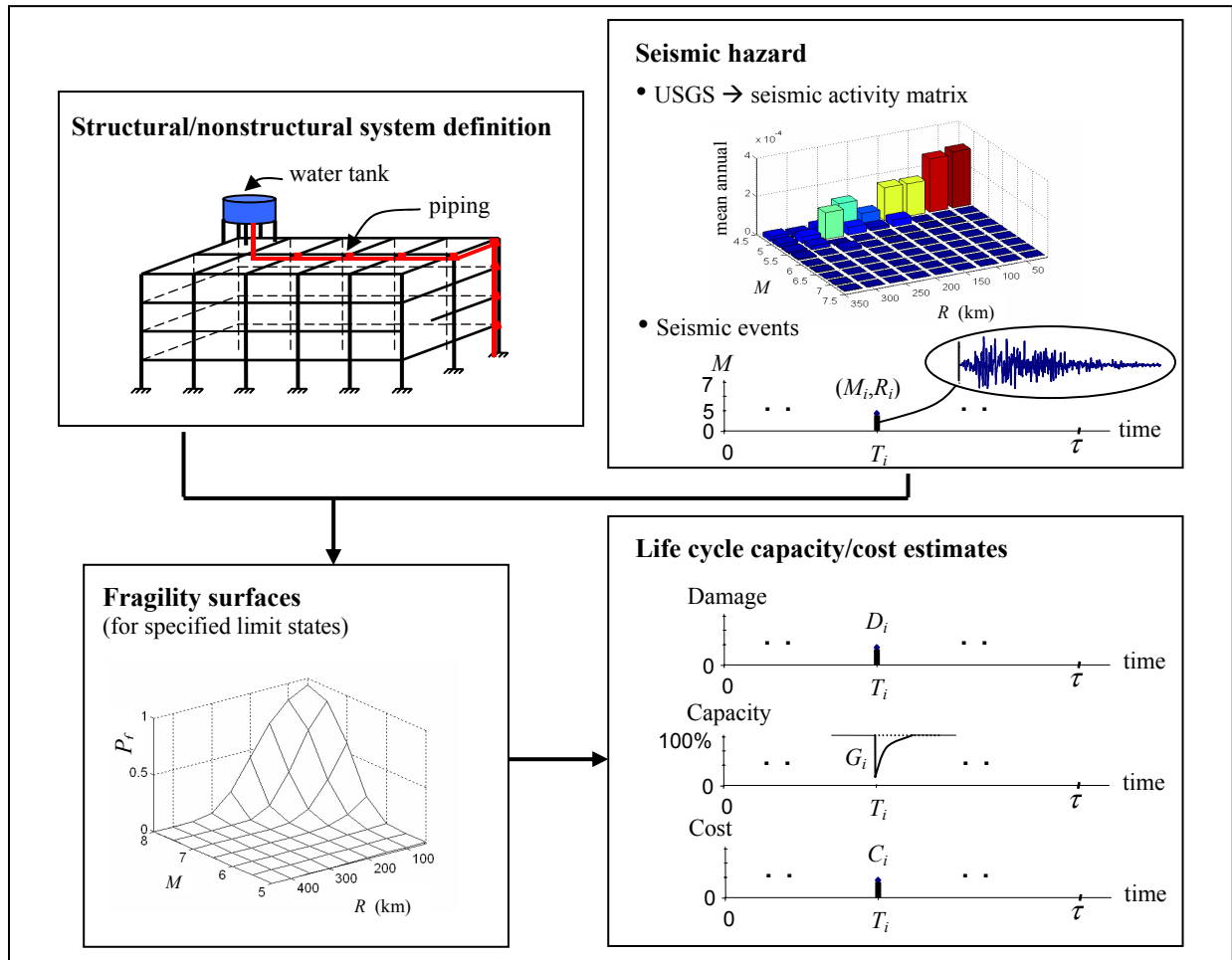


Figure 1. Loss estimation

### Seismic Hazard Analysis

The input to the seismic hazard model consists of (1) seismic activity matrix at the site, (2) the projected life  $\tau$  of a system, and (3) soil properties at the site. The seismic activity matrix is calculated using the deaggregated matrices available at USGS website (<http://eqhazmaps.usgs.gov/index.html>). Deaggregation matrices at a site give the percent contribution of earthquakes with different moment

magnitude ranges  $M_i$  and rings  $R_j$  to the seismic hazard at the site. USGS provides several deaggregated seismic hazard matrices for any location in the United States at hazard levels of 1%, 2%, 5% and 10% probability of exceedance in 50 years, where a hazard level is defined as the probability that a ground motion parameter (*e.g.* peak ground acceleration) exceeds a reference value during a given period of time. The mean annual rate  $\nu_{ij}$  of earthquakes from bin  $(M_i, R_j)$  can be calculated from deaggregation matrix (Kafali and Grigoriu, 2004a). A Monte Carlo algorithm can be developed for generating (i) random samples of the seismic hazard at the site during a given period of time  $\tau$  using the seismic activity matrix, and (ii) seismic ground acceleration samples for these seismic hazard samples. Each seismic hazard sample is defined by the number of earthquakes during the time  $\tau$ , temporal distribution, and magnitude and source-to-site distance of each of them.

Total number of earthquakes  $N(\tau)$  is assumed to follow a Poisson distribution with mean annual rate  $\nu = \sum_{i,j} \nu_{ij}$ , and the probability that an earthquake having a magnitude in the range  $M_i$  and coming from a source in the ring  $R_j$  can be obtained from  $P[M \in M_i, R \in R_j] = \nu_{ij} / \nu$ . The ground acceleration  $A(t)$  is modeled by a non-stationary stochastic process  $A(t) = w(t)A_s(t)$ , where  $t$  is the time,  $w(t)$  is a deterministic envelope function and  $A_s(t)$  is a stationary Gaussian process whose spectral density function is given by the specific barrier model. Input parameters of this model are the moment magnitude, source-to-site distance of the earthquake and the soil condition at the site. The description of specific barrier model and how to generate samples of ground acceleration time histories can be found elsewhere (Papageorgiou and Aki, 1983 a and b; Kafali and Grigoriu, 2003a). Figure 2 shows (i) the deaggregation matrix for 1% probability of exceedance in 50 years, (ii) the seismic activity matrix, and (iii) a sample of seismic hazard scenario over a life time of 50 years, for New York City (NYC) area.

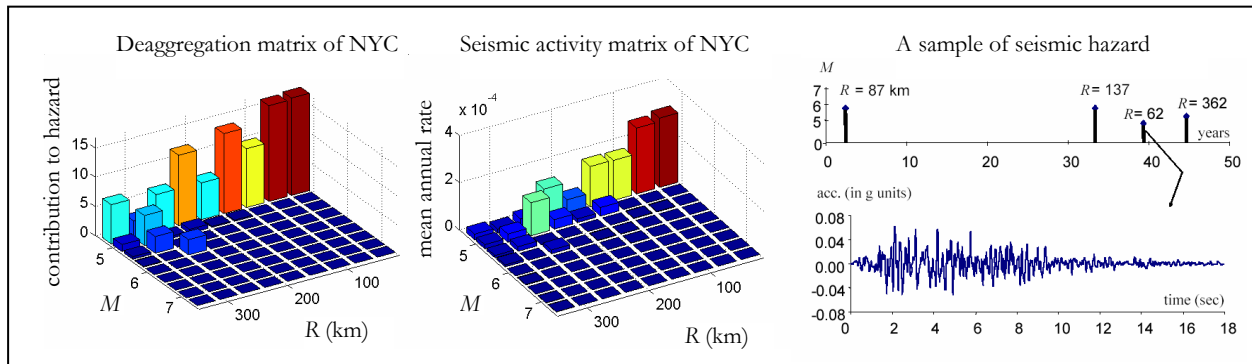


Figure 2. Seismic hazard

### Fragility Analysis

The probability that a system response exceeds a limit state viewed as a function of  $M$  and  $R$  is called system fragility surface. Monte Carlo simulation and crossing theory of stochastic processes can be used to calculate fragility surfaces of linear/nonlinear systems and their components for different limit states (Kafali and Grigoriu, 2003b, 2004b). Fragility is used to characterize the damage in the structural/nonstructural systems. Let  $D_i$  be a discrete random variable characterizing the damage state of a nonstructural system after seismic event  $i$  characterized by  $(M_i, R_i)$ ,  $i=1, \dots, N(t)$ , where  $N(t)$  is the number of seismic events in  $[0, t]$ . Assume that the nonstructural system is in damage state  $d_k$  with probability  $p_{k,i}$  for  $k=1, \dots, n$ , where  $n$  is the number of damage states. The probabilities  $p_{k,i}$  are obtained from the fragility information of the nonstructural system and are functions of the limit

state defining the damage state  $d_k$  and  $(M_p, R_i)$ . Similarly, we can define random variables characterizing the damage in structural system and components of the selected nonstructural system.

### Capacity and Cost Estimation

Capacity, for example patient per day capacity in a service, and total cost are estimated for the case of no rehabilitation and for different retrofitting techniques. Using these estimates efficient solutions can be determined. We assume that loss of capacity is caused solely by damage of nonstructural systems. The capacity at time  $t$  is

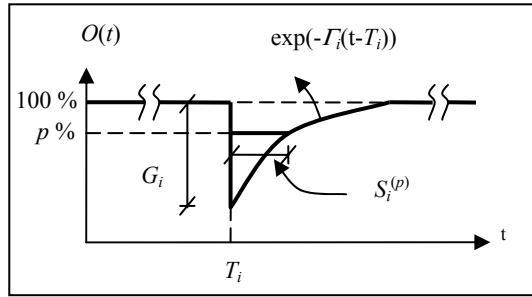


Figure 3. Capacity model

$$O(t) = 1 - \sum_{i=1}^{N(t)} G_i \exp(-\Gamma_i(t - T_i)),$$

where  $T_i$  is the arrival time of event  $i$ ,  $G_i$  and  $\Gamma_i$  are the loss in the capacity and the rate of recovery, after event  $i$ , respectively (Fig.3). Note that

$$S_p(t) = \sum_{i=1}^{N(t)} S_i^{(p)},$$

represents the total time the system spends at or below  $p\%$ -level capacity in  $[0, t]$ .

The cost relates to (i) structural failure, (ii) retrofitting, (iii) repair, (iv) loss of capacity in services, and (v) loss of life. Rehabilitation is only considered for the nonstructural system. Costs due to (i), (iii), (iv) and (v) are random. The total cost in dollars at time  $t$  in net present value is

$$TC(t) = ic + \sum_{i=1}^{N(t)} C_i / (1 + dr)^{T_i},$$

where  $ic$  is initial cost related to the rehabilitation,  $dr$  is the discount rate,  $T_i$  is the time of arrival of event  $i$ , and  $C_i$  is the cost related to event  $i$ . Assume that  $C_i = CS_p$ , if structure fails and  $C_i = CR_i + CC_i + CL_p$ , otherwise.  $CS_i$  is the cost related to structural failure,  $CR_i$  is the repair cost of the nonstructural system,  $CC_i$  is the cost due to the loss in capacity, and  $CL_i$  is the cost of life losses. It is expected that with an increasing initial cost  $ic$ , the cost  $C_i$  due to event  $i$  will decrease and for some rehabilitation alternative we will have the optimum solution.

### Numerical Example

An MCEER Demonstration Hospital Project located in NYC is used to demonstrate the proposed methodology. Three different levels of rehabilitation, namely, (i) no rehabilitation (rehab.1), (ii) life safety (rehab.2) and (iii) limited downtime (rehab.3) are considered. It is assumed that the structure is linear elastic and cascade analysis applies, that is, the nonstructural system does not affect the dynamics of the supporting structure. The nonstructural system considered consists of a water tank (comp.1) and a power generator (comp.2) located at the roof and at the first floor, respectively. It is assumed that (i) the components are not interacting, (ii) water tank is drift sensitive, (iii) power generator is acceleration sensitive, and (iv) both components are linear single degree of freedom oscillators. An illustration of the hospital model with two components attached to it, the required

modal properties of the structure (damping ratio is 3% for all modes), and natural frequencies and damping ratios of the components for the different rehabilitation alternatives are show in Figure 4.

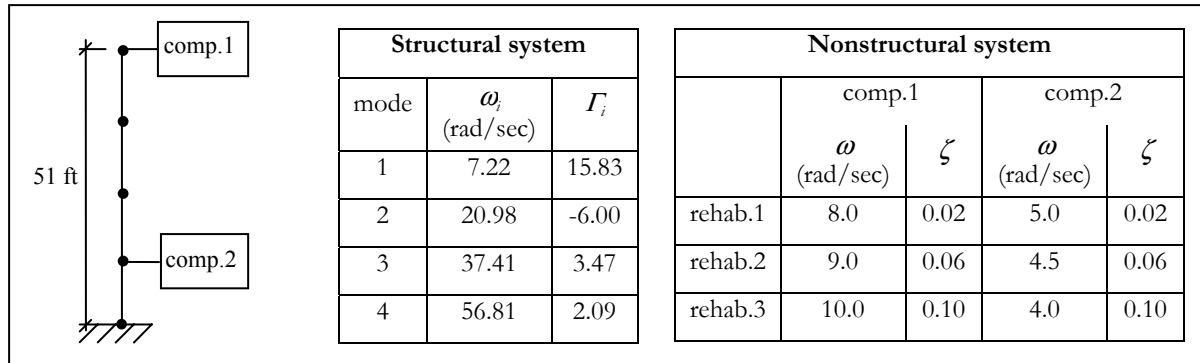


Figure 4. System properties

Fragility surfaces are obtained for the structural/nonstructural systems, comp.1 and comp.2 for different limit states assuming stationary ground accelerations. Structural system is assumed to fail when the roof displacement exceeds 5". Limit states are {0.12",0.25",0.50"} and {1.0g,1.5g} for comp.1 and 2, respectively. The nonstructural system has three damage states (i) no damage, when both components have no damage; (ii) extensive damage, when either of its components fails; and (iii) moderate damage, otherwise. Figure 5 shows fragility surfaces of structural/nonstructural systems and comp.1 and comp.2 for different rehabilitation alternatives and limit states.

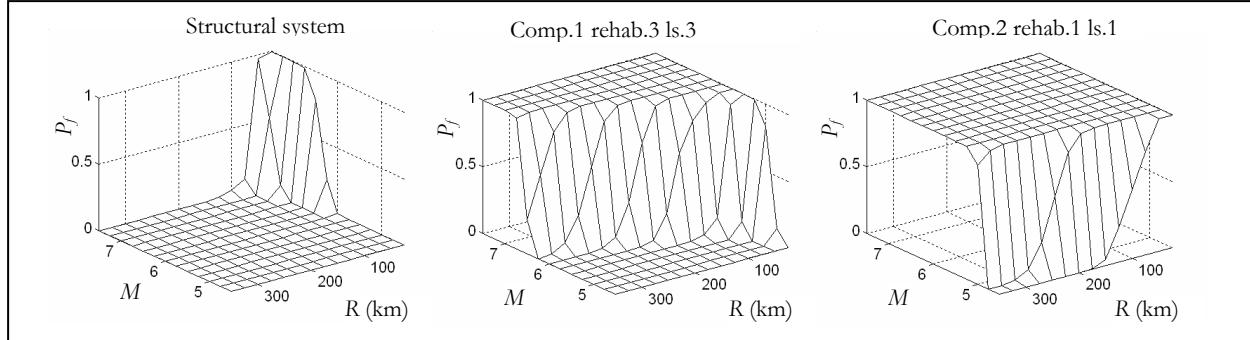


Figure 5. Fragility surfaces

Estimates of the total time the system spends at or below 80%-level capacity and the total cost  $TC$ , during a projected life of  $\tau=100$  years, for the three rehabilitation alternatives are obtained by Monte Carlo simulation. Following information is used to obtain these estimates.  $G_i$  and  $\Gamma_i$  are discrete random variables taking values {0,0.5,0.9} and {0,0.5,0.3}, respectively, with probabilities obtained from the nonstructural system fragility. The discount rate is 7% and the rehabilitation cost  $ic$  takes values {0,1000000,5000000}, for no rehabilitation, life safety and limited downtime rehabilitation, respectively.  $CR_i=C_{1,i}+C_{2,i}$  where  $C_{1,i}$  and  $C_{2,i}$  are discrete random variables taking values {0,600000,1400000,2000000} and {0,500000,1000000}, respectively, with probabilities obtained from the corresponding component fragility surfaces, and they represent the repair costs for comp.1 and 2, respectively.  $CS_i=c_s.q_s$  where  $c_s=47000000$  is the cost related to the downtime and the construction of a new facility and  $q_s$  is the probability of system failure obtained from the structural

system fragility.  $CL_i = cl \cdot X_i$ , where  $cl = 2200000$  is the cost of one person's life loss and  $X_i$  is a binomial random variable with parameters  $n_x = 100$  and  $p_x = 0.1$ , representing the number of people losing their lives, respectively.  $CC_i = \alpha \cdot RT_i$ , where  $\alpha = 2300$  is the cost due to the loss in capacity per day and  $RT_i$  is the time to reach 100% capacity given by  $RT_i = 0$  for  $G_i = F_i = 0$ , and  $RT_i = -\ln(0.001/G_i)/F_i$  otherwise. Figure 6 shows  $P(S_p(t)/\tau > s/\bar{t})$  and  $P(TC(t) > c)$ .

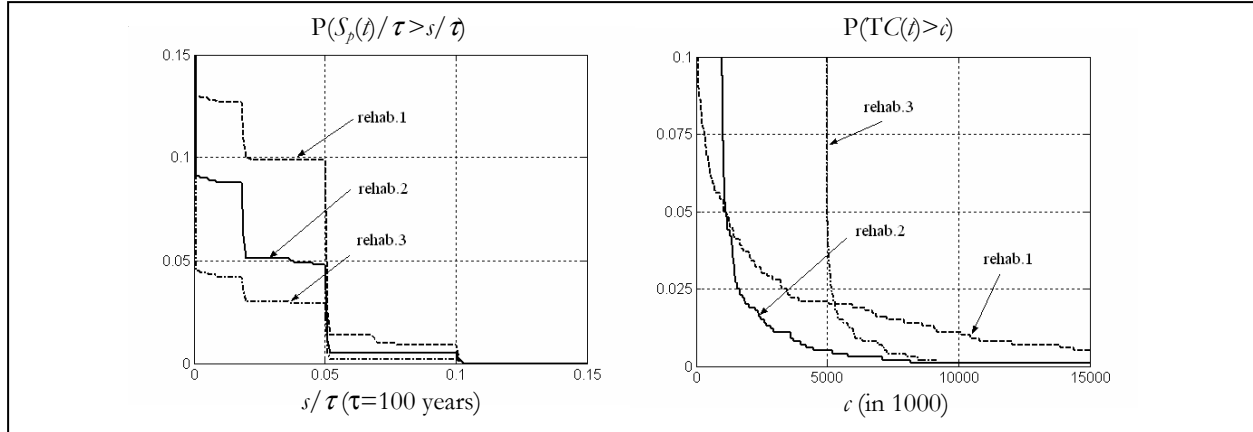


Figure 6. Estimates of the capacity and total cost

A possible measure for comparing the effectiveness of different rehabilitation alternatives is the probability that the total cost exceeds a level  $c$ . Accordingly, the optimal solution is the one with the lowest  $P(TC(t) > c)$ , and depends on the selected value of  $c$  (see Fig.6). For example, the optimal solutions are rehabilitation alternatives 1 and 2, for  $c = 500000$  and  $c = 4000000$ , respectively.

### Concluding Remarks

A method was developed to identify an optimal retrofitting technique for structural/nonstructural systems. The method (i) considers a realistic seismic hazard model rather than using the maximum credible earthquake, (ii) includes all components of costs, that is, the costs related to the structural failure and downtime, retrofitting, repair, loss of capacity in services, and loss of life, and (iii) is designed for individual facilities rather than a large population of them. The method is based on Monte Carlo simulation, probabilistic seismic hazard, fragility surfaces and capacity/cost analyses.

### Acknowledgements

This research was carried out under the supervision of Dr. M. Grigoriu, and supported by the Multidisciplinary Center for Earthquake Engineering Research under NSF award EEC-9701471.

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