FLOW-BASED RELIABILITY ASSESSMENT OF INFRASTRUCTURE SYSTEMS

Leonardo Dueñas-Osorio[†] and Isaac Hernandez-Fajardo[‡]

[†]*Assistant Professor,* [‡]*Doctoral student, Department of Civil and Environmental Engineering, Rice University, Houston, TX. USA*
Email: leonardo.duenas-osorio@rice.edu, idh1@rice.edu

ABSTRACT

The Reliability assessment of lifelines subjected to external hazards is critical to protect the functionality and quality of utility services in contemporaneous society. This paper introduces two performance metrics to assess service reliability of systems. Service Reduction (SR), and Weighted Service Reduction (WSR) are proposed to study the potential of networked systems to meet required demands when they are subjected to external events such as earthquake hazards. These metrics provide flow-based reliability estimates of network performance that go beyond traditional connectivity-based system reliability methods. Using Monte Carlo simulation and flow optimization algorithms, probabilistic fragility curves for a practical networked system in Memphis, Tennessee, USA are generated. Comparison of trends in the predicted behavior of the testbed system under connectivity and flow-based functionality performance measures highlight the adequacy of the new metrics to capture quality of service at the customer level. In fact, results from WSR reveal that it is possible to maintain adequate levels of service for higher levels of seismic intensity if a targeted flow assignment strategy is implemented. The proposed fragility curves of infrastructure system's service reduction can be used for decision making processes involving pre-disaster maintenance activities and post-event interventions. Flow-based fragility curves can also be employed as tools for the assessment of retrofitting actions by comparing network reliability predictions before and after the implementation of strategic topological and structural enhancements.

KEYWORDS: System, fragility, Service reduction, Earthquake hazard, Simulation, Optimization.

1 INTRODUCTION

Reliability of lifelines system is a complex task due to their geographical spread, the uncertainty associated to the failure modes of its components and the influence of eventual failure of components in the global response. Hence, the study of the response of lifelines is a critical research task. The consequences of the occurrence of an event involving temporal loss of service have probed to be extremely expensive evidenced by recent massive blackouts and aging infrastructure failures (Hauer and Dagel, 1999). In order to tackle this problem, several network research approaches have been developed. Wagner et al. (1988) introduced metrics, algorithms and implicit mathematical abstraction to the study of the reliability of connection between points in a water system. Following this trend, Quimpo and Wu (1997) modeled water systems using a strategy of network decomposition as series-parallel system. Studying the reliability of such paths, they were able to generate spatial reliability plots for the connection between points in the system. Song and Der Kiureghian (2003) used a linear programming tool to study the reliability of the connectivity of a system incorporating data on probability of failure of components as constraints in a mathematical optimization framework. Shinozuka et al. (1998) proposed a methodology to study reliability of systems using simulation. They applied that methodology to a real power system using a connectivity loss metric and a complete flow model. Their strategy allowed them to generate probability of exceedence curves for the system under seismic actions. The use of complete flow models allow them to study the probabilistic service reduction of the power system. Hwang et al. (1998) applied developments from (Shinozuka et al., 1998) to a water system. They enhanced the procedure by including liquefaction potential to the hazard analysis. Adachi and Ellingwood (2008) used a connectivity-based approach to study the potential flow reduction in a water system under the action of seismic hazard and interdependence effects from a damaged power system. Ostfeld (2001) used a customized model of a water distribution system to study its reliability taking into account the variability of demands and supply, effects of backup, failure events and replacement times into the overall response.

This paper introduces an alternative solution to the study of the functionality reliability of lifelines. This solution consists on procedures employing optimization techniques to find optimal distributions conducing to satisfy as much demand as possible when the network has been perturbed. This strategy uses efficient optimization algorithms to solve minimum cost flow problems in a network, avoiding the use of detailed model, but capturing the ability of the system to satisfy its demands under the action of an external hazard. This strategy facilitates a fast simulation-based probabilistic assessment of generic networked systems, which only requires basic data of the structure and flow-related properties of the network under study. The final products of the proposed strategy are fragility curves representing the probability of exceedence as a function of hazard intensity for diverse system performance values. These curves have proved to be instrumental in decision making processes intended to design policies for pre-disaster activities as well as post-event mitigation measures. Also they can be used as an a priori tool to the evaluation of retrofitting strategies by comparing the change on the system's fragility before and after the implementation of such strategies.

2 RELIABILITY ASSESSMENT OF LIFELINES SYSTEMS

Two major paradigms guide most of the efforts to analyze civil networked systems: *Connectivity* and *Functionality*. *Connectivity* deals with the reliability of having connection paths from generators to distribution nodes. For a distribution node, its probability of being served increases with the number of paths from the generators to itself. Two well known strategies Connectivity Loss (CL), and Reachability Loss (RL) were introduced by (Wagner et al., 1988), modified by (Shinozuka et al., 1998) and enhanced by other authors (Dueñas-Osorio et al. (2007); Adachi and Ellingwood (2008)). CL is calculated by the following expression:

$$CL = 1 - \langle \frac{P_N}{P_0} \rangle \tag{2.1}$$

where P_N is the current number of paths, P_0 is the original number of paths and the triangular parenthesis stand for average over the entire set of distribution nodes. RL is also calculated as an average over the distribution set but assigns to a distribution node a value of 1 if the node is connected to at least one generator and 0 otherwise. RL represents the strict version of the connectivity approach whilst CL captures the slow decrease of connectivity potential. It should be noticed that the connectivity approach does not take into account the flow properties of the system, specially those referring to the capacity of its transmission links. Consequently, the *Functionality* approach intends to capture the decay in the network's ability to provide quality service. It focuses on the flow of services or goods the systems is transporting. Most of the strategies exploring the functionality paradigm use the response obtained from detailed models of the system to study the deterioration of a satisfied demand index. However, this approach usually interferes with probabilistic assessments because of the important computational effort needed to implement physics-based simulation routines. In that trend, this paper proposes an alternative to the usual solution of detailed models, by means of procedures using optimization techniques for the analysis of network flow response. Detailed models require excessive computational effort and human manipulation in the input and post-processing stages that make them undesirable for many practical cases. This works proposes two strategies, Service Reduction (SR), and Weighted Service Reduction (WSR), to analyze networks and produce optimal flow distribution patterns incorporating economical considerations and also the importance of geographical service districts. These strategies use optimization tools to find economically optimal flow distributions attempting to fulfill the demands in the distribution nodes of the network. Their implementation is relatively simple and their requirements in terms of time and computational effort make them a suitable choice for simulation-based probabilistic assessment.

3 REGULAR AND WEIGHTED SERVICE REDUCTION METRICS

Service reduction implementation requires a graph model of the network, identification of generation and distribution points, capacities and cost values of connection links as well as generated and demanded flow for the nodes of the system. With this information, a minimum cost maximum flow problem is solved. The goal is to send as much flow as available in the generators toward the distribution nodes. This task results simple when the network is intact, but the problem grows complex when its structure has been affected by hazard action. In this type of situation, an integer programming algorithm is used to find the optimal flow patterns. The Augmenting Shortest Path, (ASP), algorithm (Goldberg and Tarjan, 1989) solves a min-cost, max-flow problem by casting it into a min-cost circulation problem. This problem is solved by applying a Generic Augmenting Path algorithm (Ahuja et al., 1994) to solve a max-flow problem, using a shortest path algorithm (Dijkstra, 1959) in a residual ancillary network. SR is calculated as follows:

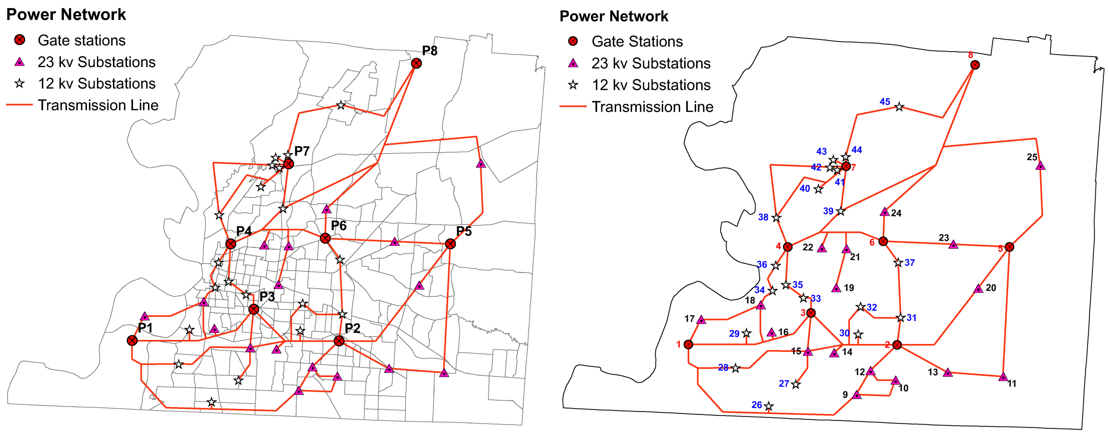
$$SR = 1 - \langle \frac{D_S}{D_0} \rangle \tag{3.1}$$

where D_s is the actual satisfied demand in a distribution node, D_0 is the original demand value and the triangular parenthesis stand for average over the entire set of distribution nodes. The worst case running time of this procedure is $O(n^3m^2)$. Weighted Service Reduction, WSR follows the same evaluation strategy of SR. However, WSR constraints the flow saturation process in SR by taking into account the importance of the service demands at the different distribution districts. WSR establishes that distribution nodes with larger values of demand must be served first than other nodes. This statement induces a prioritization bias in the flow patterns which makes WSR produce different results for the reliability assessment of the network functionality, even though, both procedures use the same reliability metric formula (3.1). The worst case running time of the WSR procedure is $O(n^4m^2)$.

4 EXAMPLE APPLICATION

The metrics discussed in this paper are applied to two test networks to compare and conclude about their merits in network reliability assessment. Two networks L and Q were generated for such task. Both systems were created to reflect a particular flow-capacity design strategy but shared a common topological structure, identification of generation and distribution nodes, as well as length of connection links and values of supply and demand in the respective nodes. L was created by solving a linear minimum cost flow problem. The flow values in the links found in such analysis are assigned as capacity of the same links. By doing so, a linear distribution of link capacities is achieved. A similar procedure followed for Q, but instead of a linear problem a quadratic min-cost flow problem is solved, resulting in a more realistic quadratic distribution of capacities for the links of the network. Because of the definition of the objective function in the optimization process, it turns out there is a spread trend in Q, i.e. Q tends to share the responsibility of flow traversal among more network links. Since the cost is scaled in a quadratic way, the links tend to have smaller values of capacity and more links are used to send flow when compared to L. The backbone structure of L and Q is taken from a test network used in (Shinozuka et al., 1998). These authors used a power network located in Shelby county, Tennessee. Figure 1a show the location of the networks and the components included in its model. Figure 1b presents the identification of the nodes to generate a directed graph model of the systems.

The earthquake hazard associated to the Shelby county area is depicted in Figure 2. This plot was generated for the most significant event consistent with 10% probability of exceedance in 50 years. The analysis process used information from HAZUS-MH (Holmes et al., 2003) and considered different seismic sources of importance for the zone.



(a) Geographical location: Shelby County, TN (b) Graph abstraction

Figure 1: Power network: representations

In order to generate a system reliability assessment, the individual fragility of the nodes of the system to the hazard action is needed. Figure 3, presents the fragility curves used for the test networks. These curves use a classification of substations in terms of the level of voltage capacity as follows: high, greater than $250\,kV$,medium, between $150\,kV$ and $350\,kV$, low, less than $150\,kV$. Gate stations are model as high voltage level substations, while the remaining ones are low voltage level substations. These vulnerability plots contain probabilities of exceedence that are conditional on the level of damage. The *Extensive* level of damage is used for the nodes of the network. Holmes et al. (2003) associates an Extensive damage state to a 70% of damage of the operational elements or the building itself of the substation. Such level of damage implies a restitution of the service in a mean time of 7 days.

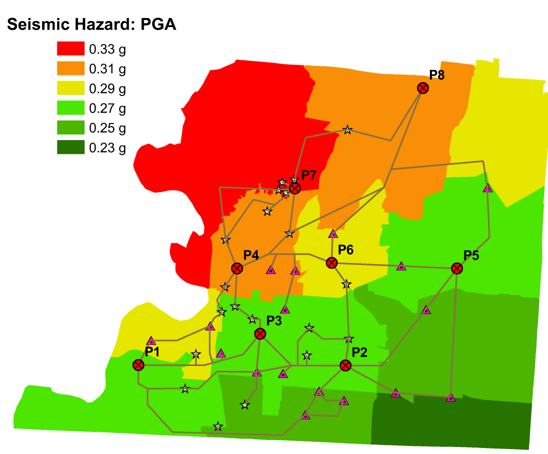


Figure 2: Distribution of seismic hazard in Shelby County, Tennessee,

Using the characterization of hazard, fragility and the capacity assignments for Q and L, a simulation-based reliability assessment was implemented. This process used 10 000 simulations of failure scenarios for levels of earthquake hazard ranging from $0.1g$ to $1.2g$. For each scenario, 4 values of performance were obtained (CL, RL, SR and WSR). This stage was followed by a statistical analysis step that produced a set of frequency of failure plots and fragility curves for levels of system's performance ranging from 0% to 100% of damage. These results, for both systems L and Q, are presented and discussed in the next section.

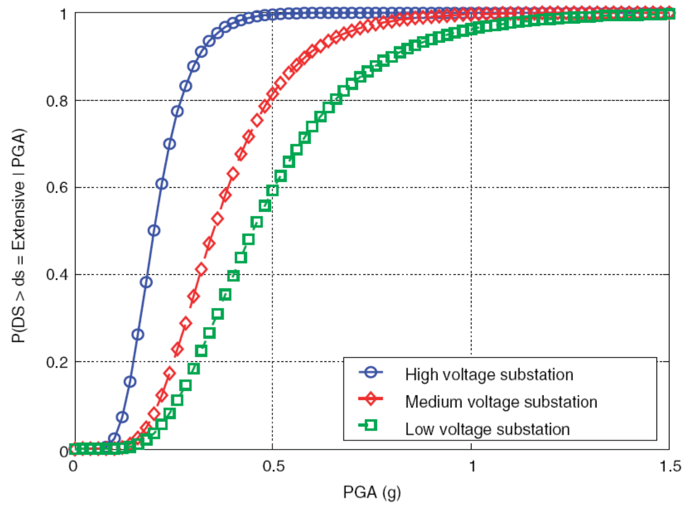


Figure 3: Fragility curves for network's nodes

5 ANALYSIS OF RESULTS

Following the computation process, a set of fragility plots in terms of the four network's metrics were generated. Special attention was placed to the generation of results of Service Reduction and Weighted Service Reduction for the response comparisons of systems L and Q.

5.1 Fragility analysis using connectivity metrics

Figure 4 shows the fragility curves for CL and RL. Since both L and Q share the same topological structure, these curves share overall trends, but possess particular features as well. CL curves are aligned toward the left, which indicates they are more fragile compared to the plot of RL. This behavior is explained by the definition of CL where the loss of a single connection path induces higher fragility. Curves for 0% and 10% performance level are depicted close to each other, showing how small perturbations produce a CL that may or may not be critical for the demand satisfaction of a distribution node.

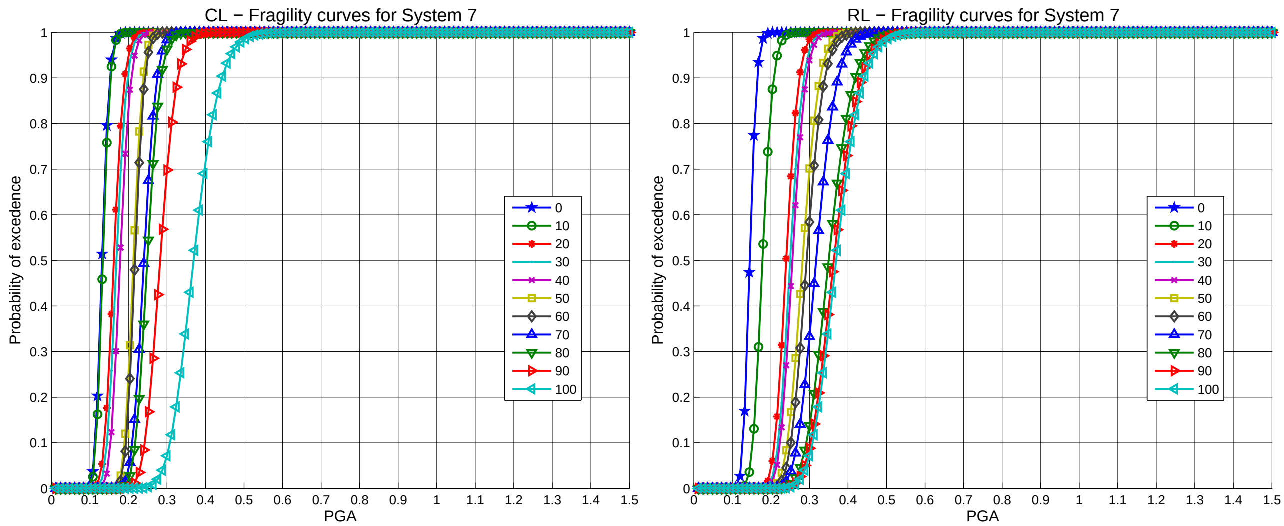
An interesting insight is obtained by checking specific values in the curves. Verifying the values of probability of exceedence for a PGA of $0.3g$, it is found that the POE for 90% damage is 0.7 whilst the value for the RL plot is close to 0.1. In this scenario, CL captures the likelihood of sequential damage whilst RL affirms that having extra damage close to the system's collapse is still unlikely. This example makes evident that although their definitions are related, the results from CL and RL offer different types of insight on the system's performance. However, such insight is limited to the information about the connection state of the system, which only in extreme performance values (0% and 100% of damage) can directly provide meaningful insight on the functionality state of the network.

5.2 Fragility analysis using functionality metrics

The following sections present the fragility description of the systems using SR and WSR. Individual plots are shown for each performance metric in order to facilitate comparisons among systems and metrics.

5.2.1 SR fragility curves for systems L and Q

SR was used for the results of this section. Calculated fragility curves are presented in Figure 5. An interesting better performance of Q at 20% damage level is the result of having a spread capacity distribution, i.e. more

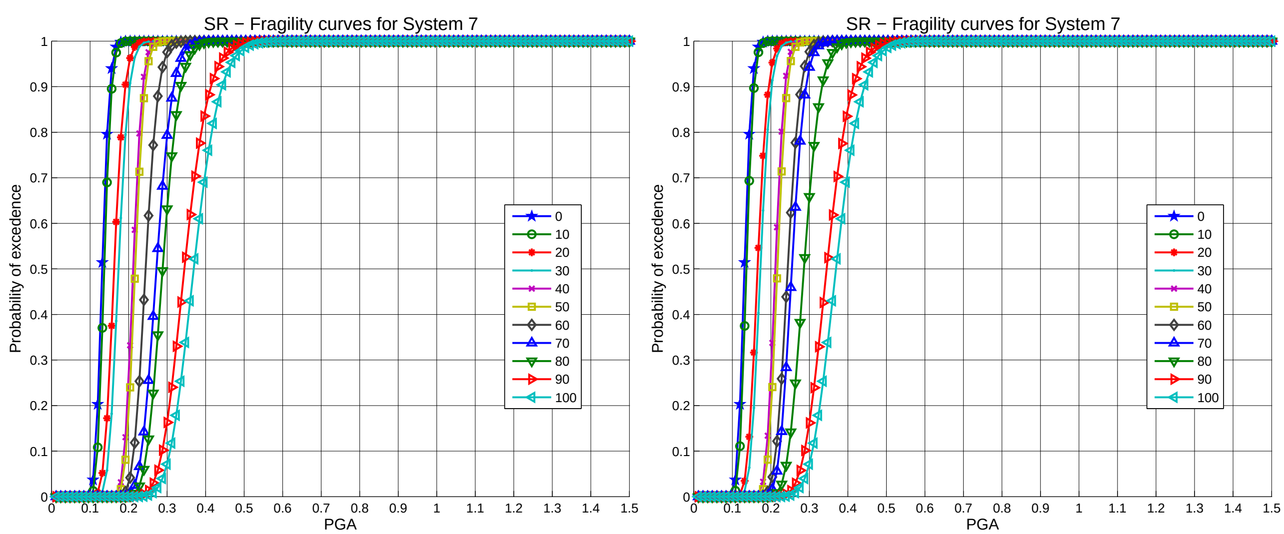


(a) CL

(b) RL

Figure 4: Connectivity (CL) and Reachability Loss (RL)

links with enough capacity to transport flow. However, such spread comes with a cost: the average capacity of the links is reduced. Since the search in SR is unbiased in terms of service providing, it appears the spread of Q's capacity distribution is being interpreted as a weakness when high hazard levels are considered. This fact explains the deterioration of Q's performance shown in curves for the 70% and 80% of damage. When higher levels of damage are involved (generated by higher levels of PGA) the capacity spread of the Q system triggers more disconnection failures that added to the natural vulnerability of the components, and the definition of SR itself, leads to a shift to a better performance of L.



(a) Linear

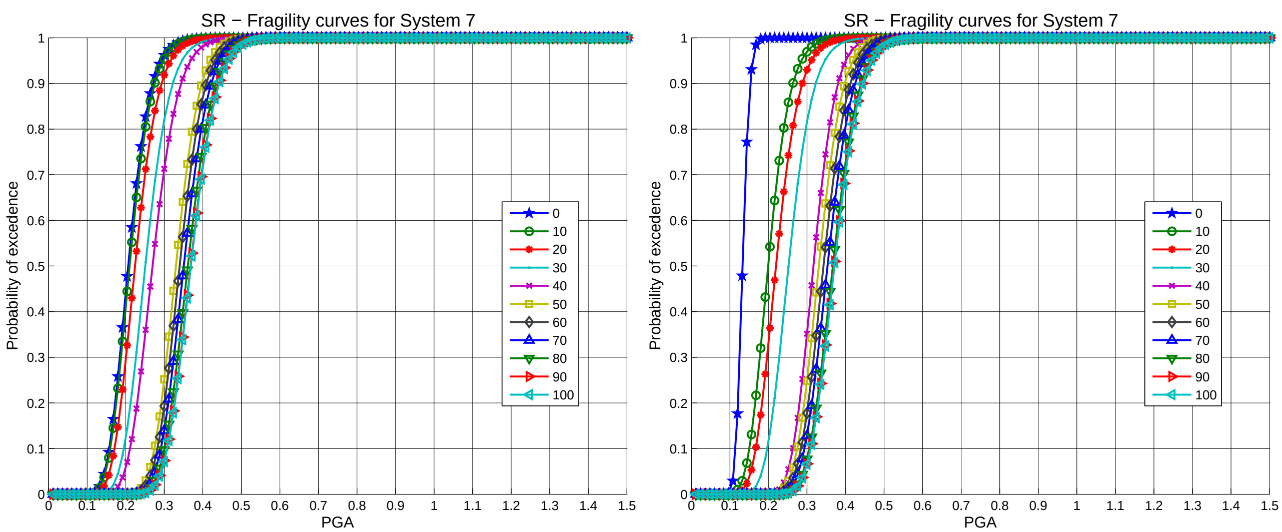
(b) Quadratic

Figure 5: Service Reduction, SR: Linear and Quadratic Capacity

5.2.2 WSR fragility curves for systems L and Q

WSR was applied to the systems L and Q in order to study their fragility and establish the adequacy of the new performance metric. Results are presented in Figure 6.

Figure 6(a) presents a different curve for the 0% performance level, less fragile than the one shared by all other plots. The lack of spread of the distribution of capacities, combined with the targeted search for the most valuable distribution nodes tends to generate an extra robust system in which larger values of hazard intensity are needed to trigger initial damage. However, this strengthening is limited to small levels of damage and its effects fade fast, as can be observed in Figures 6(a) and 6(b). Curves for 0% damage are very different, but curves for 10% and 20% look increasingly similar. The difference is almost gone at 30% damage level. From that curve on, system Q outperforms or matches L's performance. This behavior remarks the possibility of enhancing the reliability of a system only by increasing individual capacities of the most used components, at the same time remembers that such improvement will not last when larger perturbation levels occur.



(a) Linear (b) Quadratic

Figure 6: Weighted Service Reduction, SR

6 CONCLUSIONS

This paper introduced two lifeline reliability metrics to measure system's performance under a functionality approach that assesses the deterioration of network's capacity to satisfy demand for service. The nature of Service Reduction and Weighted Service Reduction as functionality metrics provide detailed insight into the behavior of networked systems. From the results shown, it is evident that the level of detail information provided by SR and WSR cannot be met by tools as CL and RL, whose scope is limited to the integrity of the system quantified through the change in the number of connecting paths. SR and WSR have closely related definitions, but their applications provide completely different insights into network's response prediction and recovery. Service Reduction is closer to a model of a normally-operating system: its definition does not explicitly differentiate the demand sectors is serving. WSR, is a closer representation of fast recovery strategies once a perturbation has taken place. Its aim of sending flow to larger demand distribution nodes first results in higher reliability due to flow pathway saturation. Also WSR could be used as a detailed strategy to reveal critical nodes for the overall behavior by modifying their vulnerability and comparing trends before and after the change. An important insight generated from the analysis of L and Q under the introduced functionality metrics, is, that it is possible to improve the behavior of a network for small levels of damage by improving the capacity of existing links. However, it was also pointed out that such enhancements not involving essential changes in the topology of the network will not last, and the system will perform as if no intervention had been executed under the action of a higher intensity event.

ACKNOWLEDGMENTS

The work reported here has been funded in part by the National Science Foundation through grant CMMI-0728040.

REFERENCES

Adachi, T. and B. Ellingwood (2008). Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability. *Reliability Engineering & System Safety 93*, 78–88.

Ahuja, R., T. Magnanti, and J. Orlin (1994). *Network flows*. New York, NY, USA: Prentice Hall.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik 1*, 269–271.

Dueñas-Osorio, L., J. Craig, and B. Goodno (2007). Seismic response of critical interdependent networks. *Earthquake Engineering and Structural Dynamics 36*(2), 285–306.

Goldberg, A. and R. Tarjan (1989). Finding minimum-cost circulations by canceling negative cycles. *ACM 36*(4), 873–886.

Hauer, J. and J. Dagel (1999). White paper on review of recent reliability issues and systems events. *Consortium for Electric Reliability Technology Solutions, CERTS*.

Holmes, W., R. Borcherdt, D. Brookshire, R. Eisner, R. Olson, and H. Lagorio (2003). *HAZUS MH MR3 Earthquake Model Technical Manual*. Washington, D.C.: Federal Emergency Management Agency. United States Department of Homeland Security.

Hwang, H., H. Lin, and M. Shinozuka (1998). Seismic performance assessment of water delivery systems. *Journal of Infrastructure Systems 4*(3), 118–125.

Ostfeld, A. (2001). Reliability analysis of water distribution systems. *Urban Water 3*, 253–260.

Quimpo, R. and S. Wu (1997). Condition assessment of water supply infrastructure. *Journal of Infrastructure Systems 3*(1), 15–22.

Shinozuka, M., A. Rose, and R. Eguchi (1998). *Engineering and Socioeconomic Impacts of Earthquakes - An Analysis of Electricity Lifeline Disruptions in the New Madrid area*. Multidisciplinary Center for Earthquake Engineering, MCEER.

Song, J. and A. Der Kiureghian (2003). Bounds on system reliability by linear programming. *Journal of Engineering Mechanics 129*(6), 627–636.

Wagner, J., U. Shamir, and D. Marks (1988). Water distribution reliability: Analytical methods. *Journal of Water Resources, Planning and Management 114*(3), 253–275.