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LIFELINE PERFORMANCE EVALUATION

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SUMMARY

Utility lifeline behavior for seismic loadings is examined for selected urban areas in the US and Japan. From the data available [e.g., Reed, et al., (2002), and Nojima, et al. (2001)], the empirically derived fragilities are examined and categorized for "ductility" and "brittleness." Analogies of lifeline network behavior with mechanical modes of failure generally labeled as "ductile" and "brittle" are made. In a general sense, "ductile" systems exhibit gradual failures widespread over time, whereas "brittle" systems experience rapid failure when placed under duress. Through these comparisons, general guidelines for evaluating networks and making improvements to increase the ductility are made.

INTRODUCTION

Electric utility lifelines are comprised of three subsystems: generation, transmission and distribution. The elements of the system are illustrated simplistically in the diagram of Figure 1. [*Distribution System Reliability*, (2002)].

Typically, reliability efforts are focused upon one of the three subsystems. For example, distribution systems are subject to particular scrutiny and standards for reliability indices have been established by IEEE. These are SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index). They are defined as follows [IEEE, (2001)]:

$$SAIDI = \frac{\sum \text{Customer hours off for each interruption}}{\text{Total number of customers served}} \tag{1a}$$

$$SAIFI = \frac{\sum \text{Customers affected by each interruption}}{\text{Total number of customers served}} \tag{1b}$$

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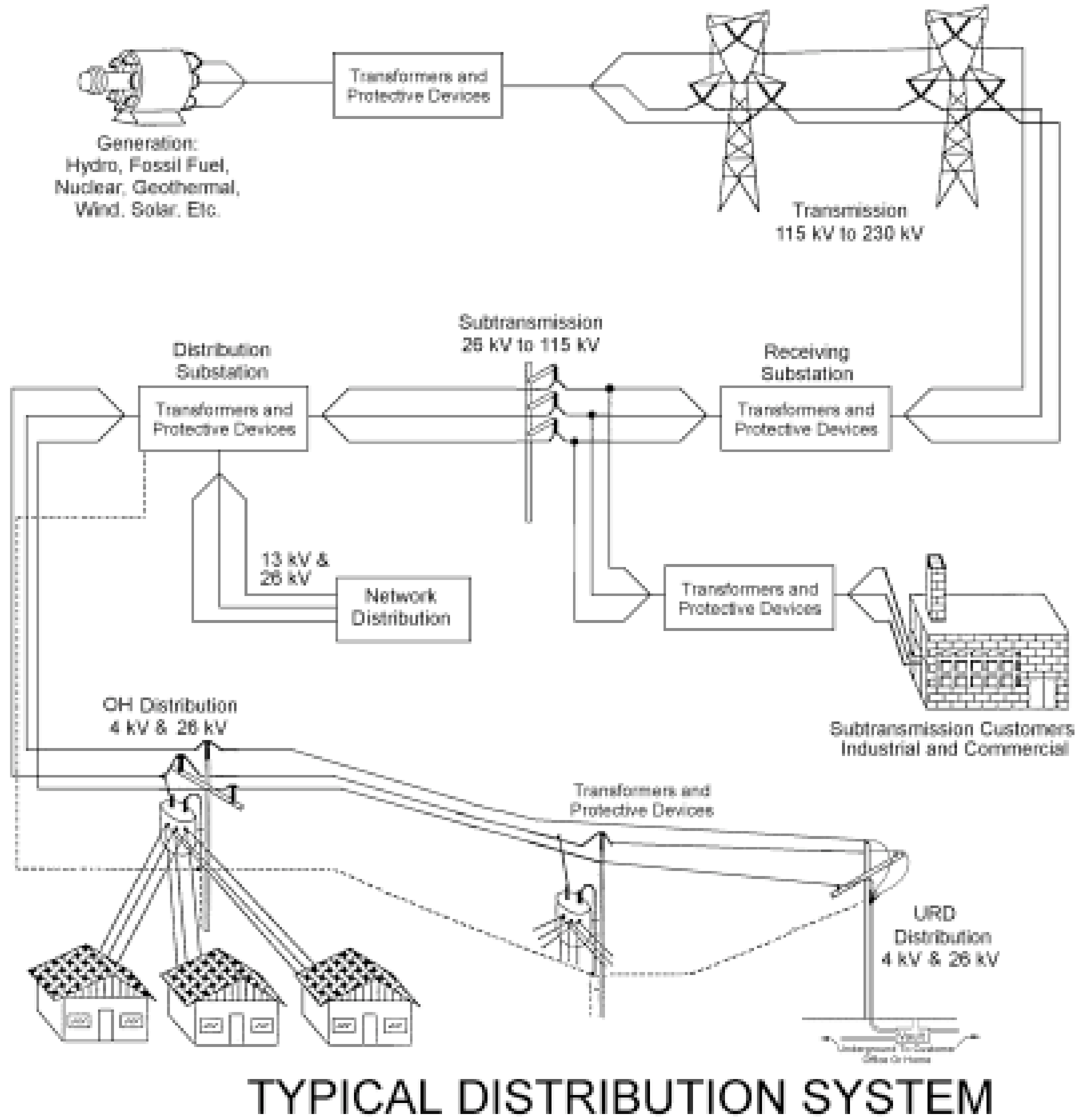

Figure 1. Simplified diagram of a typical US utility lifeline. Taken from [Seattle City Light, *Distribution System Reliability*, (2002)].

These measures of reliability are misleading and ambiguous for the following reasons: The definition of "outage" varies from utility to utility. Some do not consider outages lasting less than a minute, while others do not consider outages lasting less than five minutes in their calculation. In addition, a business may be counted as one customer whereas a household is also counted as a customer. Also, because outages may "travel" from one region to another during an event, the exact number of people affected is not truly reflected in the indices since they are not evaluated spatially or over time. Voltage drops from transmitted electricity to distribution systems generally occur at various substations. These substations have been the focus of attention since they tend to fail in shallow-focus earthquakes typical of California events.

NISQUALLY ANALYSIS

On February 28, 2001, a magnitude 6.8 earthquake struck western Washington State in the US. The epicenter was approximately 58 km southwest of Seattle. Initial estimates by the United States

Geological Survey indicated a focal depth of 60 km. The utility provided system wide outage statistics for the Nisqually earthquake. Unfortunately, specific causes of failures were not documented by the repair crews who simply noted “earthquake” rather than pinpointing components of the system that were damaged. Outages during the Nisqually earthquake event were correlated with several parameters as described in the following sections.

Restoration Rate

Restoration efforts were swift and concluded within thirty-six hours after the event. Figure 2 shows the actual restoration and the best-fit rate *R* as defined by [e.g., Chang (1998)]:

$$R = 1 - e^{-bct} \qquad (2)$$

where b = 10.06; c =1 for time t in days. In comparison, for lifelines in the Bay area following the Loma Prieta earthquake, b = 2.75 and c =1. The relatively high value for the parameter *b* in our study reflects the rapid recovery for the Seattle area.

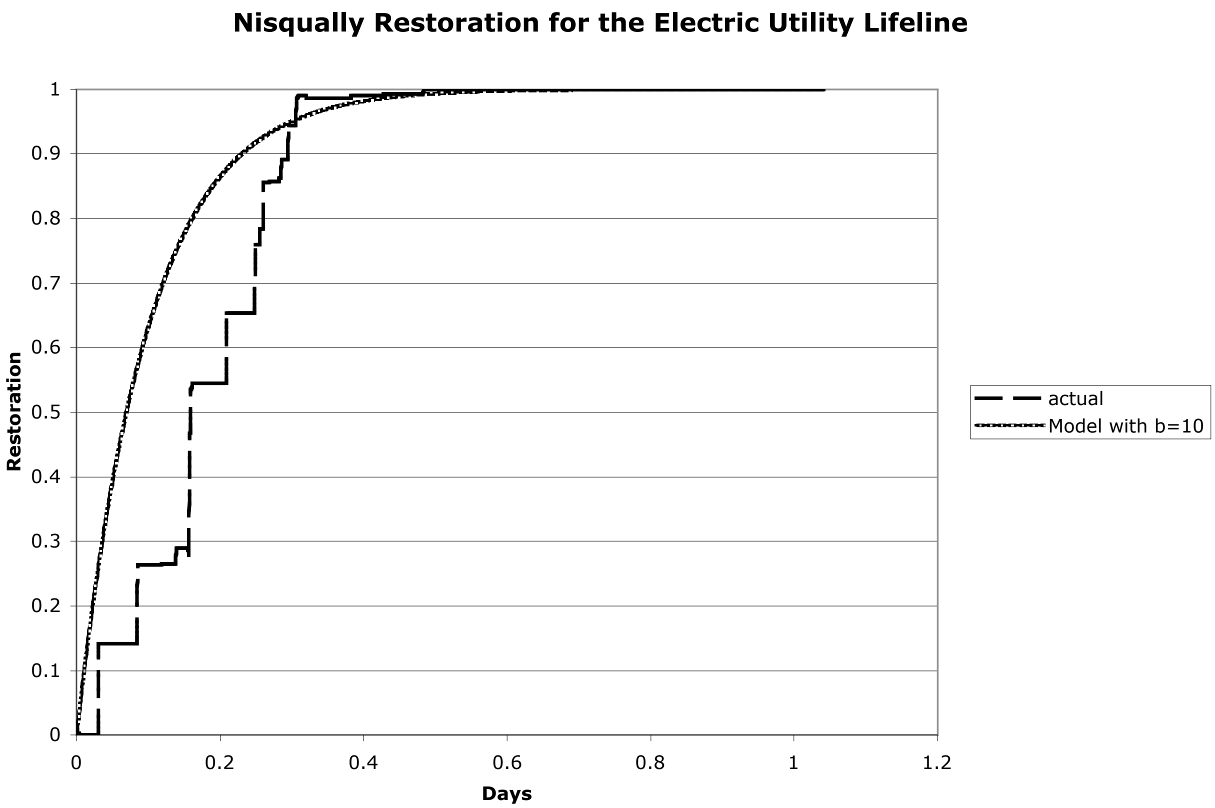

Figure 2. Restoration rate for the Nisqually Earthquake.

The restoration results are similar in form to those obtained by Nojima, and Sugito (2002) for the Great Hanshin-Awaji (Kobe) earthquake of 1995 and in the general format provided by ATC-25 [ATC (1991)]. It is noted that substations, although historically more vulnerable to seismic loadings during California events [e.g., Anagnos (1999); Hwang and Huo (1995); Schiff (1998)] did not experience significant damage during the Nisqually event. The influence of transmission system damage upon the distribution system failure was not considered in this analysis, as transmission data were not available for consideration. There were no reports of generation failure.

Outage Duration

In addition to an analysis of restoration, the probability distribution of outage durations as shown in Figure 3 was investigated. Of the recorded outages, twenty-four percent were recorded as "flickers", that is, outages of duration less than or equal to one minute or sixty seconds. In this analysis of the outage durations, the "flicker" data were eliminated from consideration.

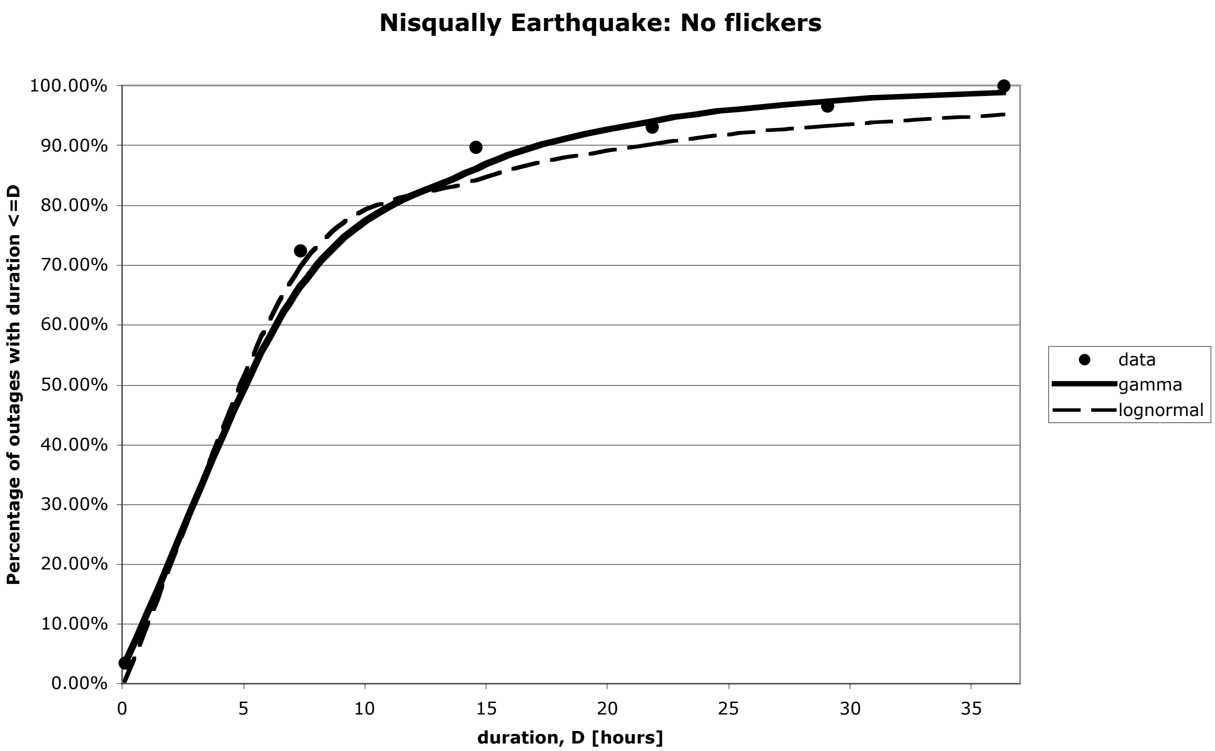

Figure 3. Outage duration analysis for Nisqually.

Previously, Nojima, and Sugito (2002) found that a Gamma distribution best fit outage data from the Kobe event. They included outages for electricity, water and gas lifelines as well. A lognormal distribution was a better fit for the Nisqually electricity data; however, it is noted that the Nisqually data set is much smaller than for the Kobe event with the maximum outage duration of approximately thirty-six hours.

Fragility Curves: Evaluation of the Damage Index

All of the outage duration data were examined for correlations with peak ground velocity (PGV), peak ground acceleration (PGA) and instrumental intensity (MMI). GIS representation of the latter three variables was obtained in *ArcView* format from the web page of the Department of Earth and Spaces Science at the University of Washington (www.ess.washington.edu/shake/). The value of the

PGA shape file is in units of acceleration of gravity or g's with the interval of the contour being 0.04g. The unit of the PGV shape file is cm/sec with the contour interval of approximately 2.0 cm/sec. The MMI shape file has a contour interval of 0.2 intensity units. Details of the computation of the instrumental MMI as based upon PGV and PGA are described in Wald, et al. (1999).

Through GIS-based comparisons similar to those described by O'Rourke, et al. (2001), damage was evaluated through an intensity factor. The *Damage Index* (DI) is defined as the ratio of the length of the affected feeders in a specific contour level to the total length of the feeder in the contour level, i.e.,

DI_i = affected feeder length in contour i / total feeder length in contour i *(3)*

The Damage Index comparison showed that about half of the feeders located in an MMI region of 7 to 8 experienced outages and a similar finding was found for PGV values greater than 22 cm/sec. The region of highest damage was located in the port area of the Seattle community that has a history of unconsolidated fill placement. In this vicinity, the Duwamish River has had the course of its flow modified significantly since 1908 [Tanner, (1991)]. Because the utility network in this region is comprised of mostly lines and poles rather than substations, it is assumed that poles are more vulnerable to base movement as described by ground velocity than acceleration. This result will be investigated further if more data become available for other earthquake events.

Logistic Regression Modeling

The damage index values were used to develop fragility curves. Based upon previous studies by Nojima and Sugito (2002), the logistic regression model was used to model the fragility. That is, the model of the conditional expectation $E(Y|x)$, where Y is defined as the damage index DI and x is the earthquake parameter such as the instrumental MMI, PGV or PGA, is sought.

The logit transformation is defined as $\pi(x) = E(Y \mid x)$ to represent the conditional mean of Y given x when the logistic distribution is used [e.g., Hosmer and Lemeshow, (2000)]. The form of the logistic regression model used is

$$\pi(x) = \frac{e^{\beta_0 + \beta_1 x}}{1 + e^{\beta_0 + \beta_1 x}} \qquad (4)$$

The logit transformation results in

$$g(x) = \ln\left[\frac{\pi(x)}{1-\pi(x)}\right] = \beta_0 + \beta_1 x \qquad (5)$$

Using the statistical software package *S-Plus*, this model was fit to the Nisqually data to yield the following tabulated results:

Table 1. Power System Models

Nisqually parameter	β_0	β_1
Log_{10}(PGA [in g's])	3.4544	6.9240
Log_{10}(PGV [cm/sec])	-10.8614	7.6203
Instrumental MMI	-17.1017	2.3824

Discussion of Fragilities

In order to evaluate the fragilities provided for the electric distribution system for Nisqually, published bridge damage data of Ranf, et al. (2001) were examined. Ranf, et al. (2001) reported that seventy-one out of a total of 8,445 bridges owned and operated by the Washington State Department of Transportation (WSDOT) were damaged. Given the latitude and longitude coordinates of the bridges, the bridge damage data were correlated with the MMI (instrumental), PGV and PGA contours. On the basis of this analysis, a logit regression model was employed for the bridge fragility curve. In terms of $\log_{10}$PGA, the values of the parameters were $\beta_0 = -0.866$ *and* $\beta_1 = 3.714$.

From this empirical analysis, the Nisqually electricity fragility was compared with that of the bridges, and the data provided by Nojima and Yamaguchi and Yamazaki (1999) for the 1995 Great Hanshin-Awaji earthquake, as shown in Figure 4, as functions of the instrumental MMI. Nojima employed the maximum likelihood model for his results using the Japanese seismic intensity parameter JMA. Numerous empirically-based relationships for converting from *PGA* and *PGV* to instrumental *MMI* exist, as well as for the seismic intensity parameter *JMA*. For example, Tong and Yamazaki (1996) suggest

$$JMA = 2.30 + 2.01\log_{10}(PGV) \qquad (6)$$

The "heavy, moderate and minor building damage data" are taken from Yamaguchi and Yamazaki (1999) in which they modeled the fragilities using the Normal distribution.

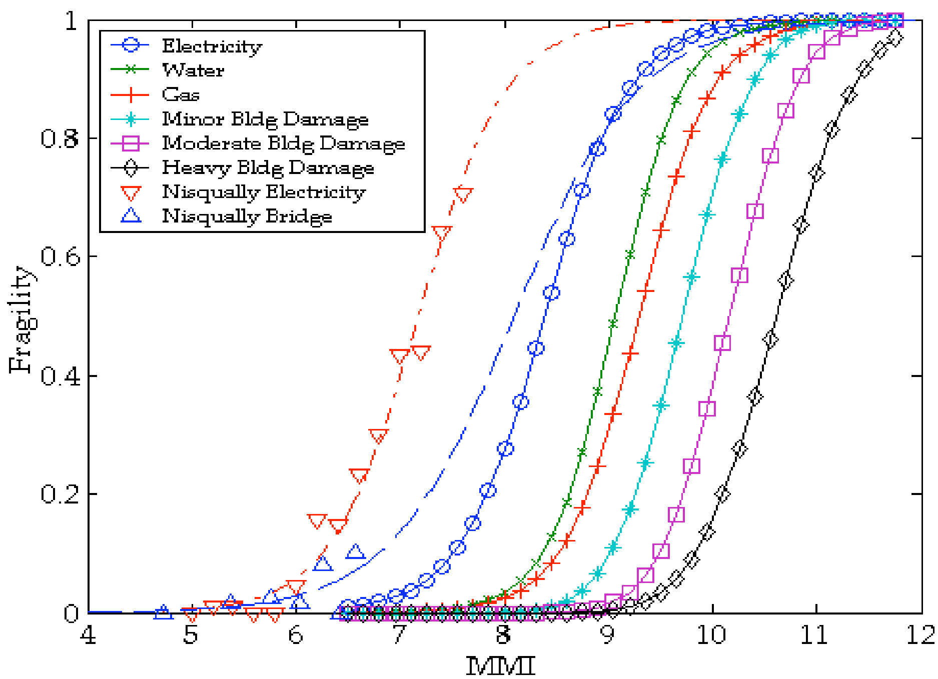

Figure 4. Fragility models of various systems in terms of instrumental MMI values. For the electricity and other utility systems, the fragility is the damage index, or percentage of feeder lines and substations experiencing damage and outages dues to the earthquake out of the total length of the lifeline at that MMI level; for bridges and low-rise buildings, the fragility is the percentage of damage anticipated as a function of instrumental MMI.

Comparative Analysis of Fragilities

The fragility analysis of Figure 4 compares network vulnerability to that of components of networks. For example, bridges are components of the transportation lifeline and the fragility curve for these components does not reflect the transportation lifeline performance directly. Werner and Taylor (2002) have studied component fragility analysis for transportation systems in detail.

When fragilities are used to evaluate network behavior, as for utility distribution, transmission or combined systems, they provide valuable information for the prediction of behavior for other seismic events. Further, they may be used to improve design or restoration planning. Dynamics students are taught early on the analogies between circuit theory and structural dynamics, but there appears to be a more productive analogy that exists between the load paths of structural systems with the flow of electrons through large-scale utility systems. Not only is flow determined by the laws of physics, the concepts of demand and capacity are strikingly similar.

In his keynote address at the CRIS conference in Beijing, Phadke (2002) called on electrical engineers to provide more innovative architectures for power lifelines. “Brittle” systems were described in this context as those where one initiating event could wreak havoc quickly for the entire network. “Ductile” systems were said to restrict disturbances and deformation without complete breakdowns for any damaging event. Phadke conceded that ductile systems are more complex to design and build than brittle ones. He did not comment on a “design-for-repair” strategy; that is, to “allow” for wires down failures to occur in the system prior to heavily loaded wires remaining intact and causing tower collapse as seen in northeastern US ice storms. Tower collapses are much more costly and difficult to repair than “wires down”. In addition, analogies of weakest-link systems can be made for this brittle-ductile behavior model; however, this is overly simplistic since the systems have load-path redundancy and are not actually of the weakest-link type.

Consideration of reinforced concrete beam design seems appropriate [e.g., Leet (1982)]. When a beam is under-reinforced, its failure mode is said to be “ductile”. Design involving over-reinforcement is said to be “brittle”. That is, if one does not understand the physics of the structural system, adding more steel reinforcement to bolster the flexural strength of a beam may actually do more harm than good. Similar results have been noted for other networks. Therefore, an examination of “reinforcement” measures for network retrofit and repair may be promising.

Dobson, et al. (2002) noted “apparently sensible efforts to reduce the risk of smaller blackouts [outages] can sometimes increase the risk of large blackouts.” Analogous situations exist for transportation systems where “demand” is traffic and “capacity increase or strengthening” the system consists primarily of creating more lanes for traffic. It is well known that increasing lanes of traffic for some urban freeways actually leads to more failures, i.e., lack of traffic “flow.” That is, the demand grows as capacity does. However, because electron flow is controlled by the laws of physics, and as yet, no one has proven that traffic is, the analogy ends with this simple comparison. In other words, for large, complex systems, the manner in which additional “strength” or “capacity” is provided to existing systems must be examined in greater detail to discern how mitigation strategies may be elucidated.

Analogies of transportation systems with topological structures of isomers in molecular chemistry have been presented by Okada, et al. (2001). Their study draws upon the work of Hosoya (1971) in molecular chemistry who identified the relationship between the topological structure of isomers and their physical characteristics such as boiling point. The nature of the arrangement is defined by a “topological index.” This index is a measure the degree of dispersiveness of a given network. The higher the index value, the more redundancy and the more decentralized the arrangement of links and nodes is said to be. It is well known that brittle materials exhibit different molecular structures than ductile ones [e.g., Hertzberg (1989)]. Also, for a given class of materials, ductility may vary significantly [Hertzberg (1989)]. An examination into the relationship of topology indices with ductility for several classes of lifelines appears to have promise for identifying arrangements that allow for more ductile behavior.

Shinozuka (2002) has used the term “seismic resilience” to characterize how rapidly a system fails; i.e., high resilience would describe a system that fails in the manner in which Phadke described “ductile” behavior: slow localized failure without affecting the entire system immediately. It is noted that the traditional materials science definition of resilience is “the measure of the amount of energy that can be absorbed under elastic conditions and which is released completely when loads are removed." [Schafer, et al. (1995)]. Hardness is defined as the "measure of a materials' resistance to plastic deformation." [Schafer, et al. (1995)].

Shinozuka (2002) attributes lifeline "resilience" to rapid search, rescue and repair efforts as well as organizational and physical robustness. Robustness can be enhanced through remote sensing and retrofitting in the pre-event stages. Continuous monitoring of the system may increase the robustness, but the cost may be too high to justify. In considering the economical, social and organizational elements of performance evaluation, Shinozuka has proposed a sample criterion for seismic events as follows: "The annual probability for a major seismic event of having more than X% of customers losing power is less than Y%." Although this criterion provides an engineering basis for lifeline evaluation, it ignores critical issues. How long of an outage duration will the customers endure? Who are these customers? Okada (2002) believes that the customer "class" significantly affects the restoration efforts within a given society. How does one make decisions about restoration? Further, the criterion while clear and concise does not provide details on how networks can be made more robust.

In an attempt to shed light on the ductile nature of the network, the fragility curves were examined. The two parameters β_0 and β_1 provide concise measures of the system – as opposed to component – failure for various classes of systems. For example, as β_1 increases, more of the system fails at lower PGA values; so therefore, it would be classified as less ductile as one that would enjoy a less rapid slope. Notable exceptions to this observation exist, such as steel connections. However, the notion has promise for the network evaluation. These points can be illustrated by the following figures. Figures 5a and 5b illustrate the influence of the two parameters on simple fragility relationships. The function $\pi(x)$ from eqn (4) is plotted vs. x. As the parameter β_0 increases, the curve "shifts" to the right along the abscissa. As β_1 increases, the slope of the curve is increased. This latter parameter appears to be the controlling factor for the "ductility" or "robustness" of the network. Further investigation into this concept is underway.

From a consideration of the complex issues involved with the development of performance criteria, the percentage of outage durations by classes of customers, as say identified in the building standard SEI/ASCE-7-02 (2002), might be an appropriate beginning. For example, if a criterion stated that following a major earthquake, 50% of the outages for a given category must not exceed 24 hours would be a good starting point. Engineers could then evaluate ductility demands in order to provide network systems that would display ductile behaviors as defined by Phadke.

CONCLUSIONS

Utility lifeline data examined for seismic loadings have shown that network fragility models are one of many tools for evaluating performance. Further investigation of the fragilities may yield insights into the behavior of networks under seismic loadings.

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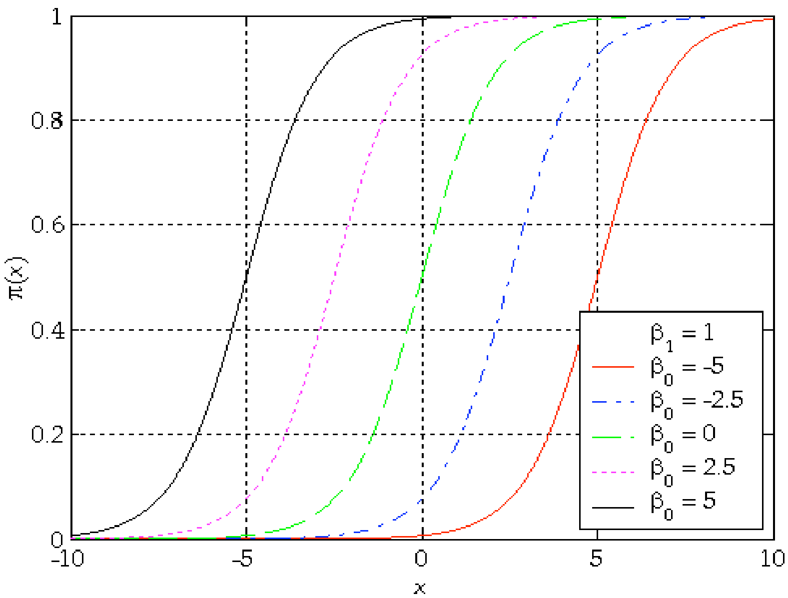

Figure 5a. The influence of the β_0 parameter in characterizing the fragility.

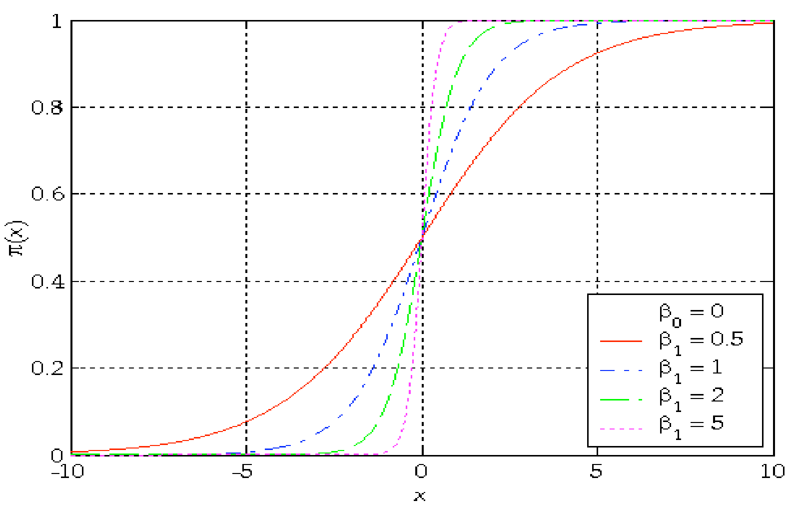

Figure 5b. The influence of the β_1 parameter on the fragility.

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