Research Objectives

The primary objective of this study is to evaluate the performance of electric power systems before and after a major catastrophic event, such as an earthquake, an accidental or manmade disablement of system components, and more importantly, incorporate the results of the evaluation as an integral part of the overarching framework of MCEER’s methodology that will enhance the seismic resilience of communities. Based on our experience in the analysis of the seismic performance of the Los Angeles Department of Water and Power (LADWP) system after the Northridge earthquake, we believe that we have derived a useful set of data and gained significant knowledge on LADWP’s system robustness during and after a catastrophic event. By employing a systematic network analysis approach, we are able to analyze the power flow status of the entire Western Systems Coordinating Council (WSCC) grid and determine the seismic performance of the entire system. Based on this knowledge, we are able to further probe the inherent weaknesses in such a system and pinpoint the weak links at the component level. In fact, our earlier studies (Shinozuka, et al., 2002 and 2003) demonstrated that retrofitting transformers sufficiently enhanced the system performance from both a safety and socioeconomic point of view.

This paper demonstrates the advances that have been achieved by MCEER’s research team and collaborative partners in dealing with electric power systems, since the publication of “Seismic Performance Analysis of Electric Power Systems” in Shinozuka et al., 1999. The advances are prominent in (1) integration of WSCC (Western Systems Coordinating Council) database with EPRI’s (Electric Power Research Institute’s) IPFLOW (Interactive Power FLOW) computer code for systematic power flow analysis, (2) development of fragility curves for transformers in a transmission network (on the basis of damage information from the 1994 Northridge earthquake and enhanced fragility curves from the test results carried out by this research team), (3) estimation of the likelihood for the power supply and for the number of households without power immediately after an earthquake, (4) development of preliminary performance criteria for
power systems, (5) application of a life cycle cost methodology to evaluate seismic mitigation for urban infrastructure systems in general, and power systems in particular, and (6) evaluation of the effect of a disabling event on the performance of a remotely located utility system.

This study evaluates the seismic performance of an electric power system, recommends appropriate seismic rehabilitation measures and estimates the associated socio-economic impact. The LADWP's power system was used as a testbed. Figures 1 and 2 show the LADWP's electric power service areas and the power supply under usual operating conditions. The areas not colored are serviced by Southern California Edison (SCE). To carry out the systems analysis, fragility curves of electrical power equipment, such as transformers in the transmission network, play an important role and are developed on the basis of damage information collected following the 1994 Northridge earthquake. Also, an equipment rehabilitation study is performed in order to examine the extent of the enhancements such rehabilitation work can produce. A systems analysis of LADWP's power system under actual and simulated earthquakes was performed. The analysis was based on an inventory database of the network, together with available fragility information of power equipment and Monte Carlo simulation techniques. This is a unique research work where an actual database from WSCC was used in conjunction with the computer code IPFLOW (version 5.0), licensed by EPRI.

Apart from the vulnerability of transformers, the seismic vulnerability of other equipment, such as circuit breakers and disconnect switches, can be and was integrated into the analysis by using corresponding fragility curves.

To gain a complete understanding of the seismic performance of LADWP’s power system, 47 scenario earthquake events were selected and simulated (discussed in detail later in this paper). These are associated with annual “equivalent probabilities” of occurrence so that collectively, they represent the full range of the regional seismic hazard. The results of this analysis produce risk curves for households without power immediately after an earthquake.

For urban infrastructure systems, evaluating the benefits and costs of hazard mitigation measures is complicated by several important considerations. First, electric power, water, and other infrastructure net-

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Perceived and actual users of the result of this research consist of utility engineers and managers, regulatory agencies, local, state, and regional emergency response agencies, civil, electrical, mechanical and systems engineers, and power equipment manufacturers. Typically, users include LADWP and SCE (Southern California Edison), California State Office and Emergency Services and Los Angeles City Office of Emergency Response.
works are spatially distributed across a wide area; hence, evaluations must account for system functionality as well as the spatial correlation of hazard (such as earthquake ground motion) across the area. Second, these systems have long service lives. Analyses must therefore consider how the system itself, as well as the potential impacts of its failure, might change over a period of many decades. Third, infrastructure systems are vital to all sectors of the urban community. Mitigation assessments should therefore include the benefits to both the lifeline infrastructure provider and society as a whole.

This paper applies a life cycle cost methodology for evaluating the effect of infrastructure mitigation techniques for seismic retrofit of LADWP’s electric power system. Total life cycle costs include repair cost, utility revenue losses and societal losses in future earthquake disasters.

Development of Fragility Curves

Failure of transformers is one of the most common and significant types of damage to electric power systems due to earthquakes. While transformers are crucial components in an electric power network, their redundancy is not as high as other power equipment due to their very large size and high cost. Therefore, it is important to make a pre-event evaluation of the seismic performance of transformers on the basis of damage information obtained from past earthquakes rather than from laboratory experi-
In this research, substantial effort was expended to acquire damage information for transmission level transformers related to the Northridge earthquake identified from one-line diagrams of the LADWP and SCE receiving stations. The damage information is transformed into empirical fragility curves expressed in the form of two-parameter (median and log-standard deviation) lognormal distribution, as a function of peak ground acceleration (PGA), which represents the intensity of the seismic ground motion at each site. Use of PGA for this purpose is considered reasonable since it is not feasible to evaluate the fragility curves as a function of spectral acceleration. This would require identification of dominant participating natural modes of vibration for each of the large number of transformers and corresponding reliable ground motion time histories. The PGA value at the location of each receiving station is determined by interpolation and extrapolation from the PGA contours (see Wald, 1998, http://quake.wr.usgs.gov/research/strongmotion/effects/shake/). In this research, the maximum likelihood method (M. Shinozuka et al., 2000) is employed to estimate the two parameters of the fragility curve resulting in $c=0.45g$ (median) and $z=0.42$ (log-standard deviation). With these two parameters, the fragility curve for the transformers in the transmission network has been developed and is shown in Figure 3 (in red) with the label Case 1.

Among possible other methods of seismic retrofit, a base-isolation technique was used here as an example. The improvements to the seismic performance of transformers are evaluated based on experimental results involving such a device. The test was performed at the NCREE (National Center for Research of Earthquake Engineering) in Taiwan under the NCREE-MCEER joint research project using NCREE’s shaking table (5 m x 5 m in plan and maximum payload 500 kN). The test had additional support from Bridgestone Corporation in Tokyo, Japan. The improvement is measured by the enhancement index defined as:

$$\text{Enhancement Index} = \frac{A_f}{A_i} - 1$$

(1)

where $A_f$ and $A_i$ are the maximum acceleration values under fixed-base and base-isolated conditions, respectively, and are both observed at six points along the transmission tank and bushing as discussed below: One point each at the bottom and top of the transformer tank, and four points along the bushing at the following locations as measured.

![Figure 3. Fragility Curves for Transformers in Transmission Network](image-url)
from the middle flange of the bushing.

- **161 kV bushing**: 1st point: -112 (cm), 2nd point: -60 (cm), 3rd point: +88 (cm), 4th point: +197.5 (cm).
- **69 kV bushing**: 1st point: -64 (cm), 2nd point: -30 (cm), 3rd point: +41 (cm), 4th point: +100 (cm).

The experiment used two types of bushings, one for 69 kV and another for 161 kV. Each was attached on the top of a rigid box-shaped frame simulating a transformer tank. In the test, three actual earthquake records were used as input earthquake ground motions: 1940 El Centro, 1994 Northridge (Sylmar) and 1995 Kobe (Takatori). Each of these records is linearly scaled in order to produce five histories with PGA equal to 0.125g, 0.25g, 0.375g, 0.50g and 0.625g, to compute the enhancement index values. However, to avoid potential significant bushing damage caused by large vibrations in the test, the records with high PGAs were not applied during the testing of the fixed-based cases. The maximum PGA for the fixed-based cases is therefore limited to 0.375g, while the maximum PGA for the base-isolated cases is 0.5g (only the Northridge ground motion record at Sylmar Convertor Station has a PGA value of 0.625g). Each bushing-tank system is subjected to the simulated earthquake records both with and without a base-isolation device. The effectiveness of the enhancement is statistically shown in Figure 4. Table 1 gives the statistical characteristics of the enhancement index from a sample size of 56 for 69 kV and 71 for 161 kV bushings. More detailed statistical analysis is being carried out grouping the acceleration records at each spatial point of measurement. Both Figure 4 and Table 1 show that the improved seismic performance of the transformers is very significant, with a mean value of enhancement index ranging from 1.6 to 3.5. Therefore, in the following analysis, the 50% and 100% enhancement index values are considered to be achievable and are used. However, no change in log-standard deviation is considered. The enhanced fragility curves are also plotted in Figure 3 (blue and green for 50% and 100% enhancement, labeled as cases 2 and 3, respectively).

<table>
<thead>
<tr>
<th>Figure 4. Statistical Distribution of Enhancement of Transformers with the Base-Isolation Device</th>
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<table>
<thead>
<tr>
<th>Table 1. Statistical Characteristics of Enhancement Results</th>
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<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>69kV System</td>
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<tr>
<td>161kV System</td>
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<tr>
<td>Combined</td>
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</table>
Seismic Performance of LADWP’s Power System

The LADWP’s network is part of the very large WSCC’s (Western Systems Coordinating Council’s) power transmission network, which covers 14 western states in the U.S., two Canadian provinces and northern Baja California in Mexico. The present analysis is performed by taking all the receiving stations and transmission facilities covered by the WSCC network into account. Parenthetically, it is noted that the WSCC’s network has been expanded to add some additional components and is presently referred to as WECC (Western Electricity Coordinating Council, http://www.wecc.biz/main.html). The proposed analysis methodology to predict the seismic performance of the electrical power network is described below:

2. For each scenario earthquake, simulate equipment damage using fragility curves with and without rehabilitation
3. Simulate damaged transmission networks
4. Calculate power flow using IPFLOW under network failure criteria
   - Imbalance of Power
     \[ 1.05 < \frac{\text{total supply}}{\text{total demand}} < 1.1 \]  
   - Abnormal voltage
     \[ \left| \frac{V_{\text{intact}} - V_{\text{damage}}}{V_{\text{intact}}} \right| > 0.1 \] 

![Figure 5. PGA under Northridge Earthquake](image)

![Figure 6. Relative Average Power Output with only Transformers Vulnerable](image)
• Frequency change
  (IPFLOW does not check this)
• Loss of connectivity

5. Compute reduction in average power supply (total and for each service area)
6. Compute relative number of households without power
7. Develop seismic risk curves (annual probability that system performance will be reduced by more than a specified level due to earthquake)
8. Examine system performance relative to performance criteria with and without rehabilitation
9. Determine effectiveness of rehabilitation

By applying the systems analysis procedures, LADWP’s power flow analysis is performed 20 times on the network for each scenario earthquake. Each simulation result represents a unique state of network damage. Figure 5 shows the PGA distribution associated with the Northridge earthquake in LADWP’s service areas. Figure 6 shows the ratio of the average power supply of the damaged network to that associated with the intact network for each service area when only transformers are considered as vulnerable. The average is taken over the entire sample size equal to 20. The extent to which the rehabilitation of transformers contributes to improvement of system performance is evident if the power supply ratios under Case 1 (not enhanced), Case 2 (50% enhanced) and Case 3 (100% enhanced) are compared (see Figure 6).

Aside from transformers, there is important electrical equipment in the power network which are also vulnerable to earthquakes, such as circuit breakers and disconnect switches. Figures 7 and 8 show the seismic performance analysis results involving these equipments, using the same fragility characteristics as for the transformers. The results show that if transformers and circuit breakers (Figure 7) or transformers and disconnect switches (Figure 8) are considered to be vulnerable under earthquakes, the power output is significantly reduced throughout LADWP’s service areas under the Northridge earthquake. This result matches the actual outcome in the 1994 Northridge earthquake. It is noted that the black-out was short-lived, due to effective restoration management on the part of LADWP. It is also notable that the actual recovery process followed the pattern of power supply restoration in the order similar to Figure 7 or 8 → Case

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**Figure 7.** Relative Average Power Output with Transformers, Circuit Breakers Vulnerable
1 (Figure 6) → Case 2 → Case 3. The fact that a black-out condition occurred not only for LADWP’s service area but also over several states after the Northridge earthquake demonstrates the far-reaching impact of a local system failure throughout the western grid.

**Risk Curves of LADWP’s Power System**

The locations of LADWP’s and SCE’s receiving stations relative to faults in and around the Los Angeles area indicates that many are near active faults and have a high possibility of suffering damage should an earthquake occur. In evaluating the risk and costs associated with potential future earthquakes, the performance of the power system in 47 (deterministic) earthquake scenarios was evaluated. These scenarios were developed by Chang et al., 2000, applying a loss estimation software tool, EPEDAT, which was used to generate regional ground motion patterns for a given earthquake epicenter, magnitude, and depth. The 47 events included 13 maximum credible earthquakes on various faults in the Los Angeles region and 34 smaller events of magnitude 6.0 or higher. Based on these analyses, together with their hazard-consistent probabilities, seismic risk of LADWP’s power system due to earthquake-induced performance degradation was developed in terms of a risk curve for Case 1 (no enhancement) and Cases 2 and 3 (enhancement index 50% and 100%, respectively), shown in Figure 9.

The percentage of households with and without power supply are computed as follows:

Relative number of households with power:

\[
\frac{1}{N} \sum_{n=1}^{N} \left( \frac{1}{M} \sum_{m=1}^{M} \text{Rd}(m,n) \times \text{Hshld}(m) \right)
\]

Relative number of households without power:

\[
1 - \frac{1}{N} \sum_{n=1}^{N} \left( \frac{1}{M} \sum_{m=1}^{M} \text{Rd}(m,n) \times \text{Hshld}(m) \right)
\]

where \( m \) is the service area number \((1,2,\ldots,M)\), \( n \) is the simulation number \((1,2,\ldots,N)\), \( \text{Rd}(m,n) \) is the power output ratio of service area \( m \) under simulation \( n \), and \( \text{Hshld}(m) \) is the total households of service area \( m \).
The risk curve in this study plots the expected annual probability that the system will suffer from a power supply reduction of more than a specified rate, as a function of that rate. Each data point in the figure represents one of the scenario events. The risk curve is useful for economic impact analysis of the Los Angeles area as well as cost and benefit analysis to determine the effectiveness of enhancement technologies. Of equal importance is the use of the risk curve in relation to the development of the performance criteria and their verification as described in the following section.

### System Performance Criteria

The performance criteria for power systems listed in Tables 2 and 3 demonstrate a possible format in which the criteria can be given. Table 2 lists criteria to be satisfied in pre-event assessment, and Table 3 lists those in post-event emergency response. These tables also include performance criteria for water and acute care hospital systems. In combination, they conceptually establish the degree of community resilience in terms of robustness, rapidity and reliability. Specific values (in percentages for

| Table 2. Statistical Performance Criterion I for Pre-event Assessment and Rehabilitation |
|----------------------------------------|----------------------------------------|
| **Robustness and Resourcefulness** | **Reliability** |
| Power | A majority (at least 80%) of households will have continued power supply after earthquake | With a high level of reliability (at least 99% per year) |
| Water | A majority (at least 80%) of households will have continued water supply after earthquake | With a high level of reliability (at least 99% per year) |
| Hospital | A majority (at least 95%) of injured or otherwise traumatized individuals will be accommodated in acute care hospitals for medical care | With a high level of reliability (at least 99% per year) |
robustness, rapidity in restoration and reliability) are examples included to better understand the concept. The performance criterion for power systems shown in Table 2 is represented by a point double-circled in Figure 10 (enlarged version of Figure 9), where the robustness corresponds to the annual probability that 80% or more households will have power immediately after any earthquake is equal to 0.99. The risk curve for Case 1 (without rehabilitation) does not satisfy this criterion, but the risk curves for Case 2 and Case 3 (with rehabilitation) do satisfy it. These criteria can also be used to judge the effectiveness of rehabilitation as carried out in this study. Data collection and modeling for rapidity in restoration are much more difficult to pursue. Further research is needed to develop analytical models based on past experience so that performance criteria, such as those shown in Table 3, become meaningful in practice.

### Evaluating Mitigation of LADWP’s Power System

The evaluation of seismic mitigation for urban infrastructure systems is carried out by applying the life cycle cost method, particularly to LADWP’s power system used in this study. The word “mitigation” here is used in a much broader sense than “rehabilitation.” The latter refers to specific seismic retrofit of systems and their components, as described below. In contrast to more traditional benefit-cost analysis, the life cycle cost framework readily and transparently accommodates costs that may change over time. For infrastructure systems, this is advantageous for addressing

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**Table 3. System Performance Criterion II for Post-Event Response and Recovery**

<table>
<thead>
<tr>
<th>Robustness and Resourcefulness</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td></td>
</tr>
<tr>
<td>A majority (at least 95%) of households will have power supply as rapidly as possible within a short period of time (3 days)</td>
<td>With a high level of reliability (at least 90% of earthquake events).</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td></td>
</tr>
<tr>
<td>A majority (at least 95%) of households will have water supply as rapidly as possible within a short period of time (3 days)</td>
<td>With a high level of reliability (at least 90% of earthquake events).</td>
</tr>
<tr>
<td><strong>Hospital</strong></td>
<td></td>
</tr>
<tr>
<td>All the injured and traumatized individuals will be accommodated in acute care hospitals as rapidly as possible within a short period of time (1 day)</td>
<td>With a high level of reliability (at least 90% of earthquake events).</td>
</tr>
</tbody>
</table>
such issues as infrastructure deterioration and urban growth. Moreover, the framework developed here emphasizes costs that would be imposed on the community, as well as the lifeline agency, in the event of infrastructure failure in a disaster. The framework therefore allows a comprehensive assessment of mitigation benefits. Details of the methodology, along with an application to the Portland, Oregon, water delivery system, can be found in Chang (forthcoming). In this approach, the options of “mitigation” and “no mitigation” are compared in terms of their total life cycle costs. These include repair costs, utility revenue losses, and societal losses in future earthquake disasters. These costs are evaluated for a period of \( N \) years, with expected annual costs discounted to their present value. For the mitigation case, life cycle costs also include the cost of the retrofit itself.

In this paper, the case study examines mitigation of high voltage transformers using base isolation. Hence, “mitigation” is synonymous to “retrofit by base-isolation” here. The impact of the mitigation on network performance was assessed by using the results from the power flow analysis of LADWP’s power system. The total life cycle cost, \( C \), can be expressed as follows:

\[
C = C_s + \sum_t \left( C_{r,t} + C_{e,t} + C_{v,t} \right) \left(1 + y\right)^{-t}
\]

where \( C_s \) is the cost of the seismic mitigation (retrofitted) measure (assumed to take place in the initial year of analysis), \( C_{r,t} \) is expected annual earthquake repair costs in year \( t \), \( C_{e,t} \) is expected annual earthquake revenue loss to the utility in year \( t \), and \( y \) is a discount rate (assumed to be a real rate of 3%). The total timeframe of analysis is 50 years. All costs are evaluated in constant dollars, not of inflation. \( C_{r,t} \), \( C_{e,t} \), and \( C_{v,t} \) are each probabilistically aggregated over the 10 or 20 simulations of the 47 earthquake scenarios, as described above.

In the analysis, the mitigated case was represented by a weighted average of the results from the “as-is,” “50% performance enhancement,” and “100% performance enhancement” analyses. The respective weights are 0.08, 0.12, and 0.80. These weights were based on the confidence levels associated with each performance level in the base isolation testing.

The mitigation case consists of base isolating 109 transformers. Although actual data on the mitigation cost was not available, based
on our research and consultation with LADWP, a rough estimate of $60,000 per transformer was used for this analysis. Seismic mitigation cost $C_s$ is therefore $6.54$ million.

Table 4 summarizes the four cost components for the mitigated and unmitigated cases. Mitigation leads to considerable reductions in expected repair costs and revenue loss in future earthquakes. Total discounted costs to the utility agency are reduced from $1.67$ million to $0.21$ million. However, these savings do not outweigh the cost of mitigation. If societal impacts are disregarded, total life cycle costs with mitigation ($6.75$ million) are four times as large as costs in the do-nothing case ($1.67$ million), and mitigation does not appear advisable.

However, if direct economic losses are considered, mitigation appears very cost-effective. Direct economic losses are on the order of 50 times as large as the utility’s repair and revenue losses combined. If they are included in the analysis, total life cycle costs without mitigation ($97.19$ million) are 5.7 times as large as costs with mitigation. Mitigation could reduce discounted, expected direct economic loss by some $85$ million. Base isolation of the transformers appears highly cost-effective.

Table 5 presents the results if it is assumed that population and economic activity remain constant over the 50-year period (i.e., no urban growth or productivity increase). The basic finding – that mitigation is cost-effective if societal impacts are considered, but not if they are excluded – is unchanged. In this case, direct economic losses are on the order of 30 times as large as repair and revenue losses combined.

### Evaluation of Effect of a Disabling Event on the Performance of a Remotely Located Utility System

A general methodology was also developed in this study to analyze the behavior of large electric utility systems under a catastrophic event, such as a severe earthquake or an intentional disabling of system components. The focus of this analysis is to determine the impact to LADWP’s power supply capability if any of the major 500 kV transmission lines in the WSCC grid were disabled, regardless of the reason (earthquake or other hazard) or distance from the Los Angeles area. Two scenarios (A and B) involving disabled 500 kV transmission lines between Washington State and Idaho State (A) and between Washington State and Oregon State (B) are shown in Figure 11 (Scenario A) and Figure 13 (Scenario B).

<table>
<thead>
<tr>
<th>Table 5. Life Cycle Cost Results without Urban Growth</th>
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<tbody>
<tr>
<td><strong>Mitigation Cost</strong></td>
</tr>
<tr>
<td><strong>Repair Cost (discounted)</strong></td>
</tr>
<tr>
<td><strong>Revenue Loss (discounted)</strong></td>
</tr>
<tr>
<td><strong>Direct Economic Loss (discounted)</strong></td>
</tr>
<tr>
<td><strong>Total Life Cycle Costs</strong></td>
</tr>
<tr>
<td><strong>Total Life Cycle Costs without Direct Economic Loss</strong></td>
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</tbody>
</table>
more redundant segment in the grid as far as the LADWP power system is concerned. The effect of a power supply reduction to LADWP service areas comes from a power-load balance requirement within the entire WSCC system. For Scenario B, however, the disabled transmission line at the border of Washington and Oregon States is a less redundant component, and influences the LADWP power system through two 500 kV AC transmis-

![Figure 11. Disabled Location A](image1.png)

![Figure 12. Reduction in Power Supply (A)](image2.png)

![Figure 13. Disabled Location B](image3.png)

![Figure 14. Reduction in Power Supply (B)](image4.png)

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sion lines and one 500 kV DC transmission line. From Figure 14, it is seen that the entire LADWP service area is blacked out when this component is disabled. This is indeed a disaster to the LADWP service area, in spite of various redundancy and tolerance built into the system between the Pacific Northwest and Southern California.

Conclusions and Future Research

This study integrated many of the technologies developed by MCEER over the years, including GIS inventory data of the LADWP’s electric transmission systems, multiple scenario earthquakes representing the Los Angeles area seismic hazard, fragility analysis of systems, sub-systems and equipment, base isolation techniques for rehabilitation of transformers, systems analysis using WSCC’s database and EPRI’s IPFLOW computer code, life-cycle cost estimation methods, and preliminary versions of performance criteria definitions and their verification procedures. This integration leads to the capability to evaluate the performance of both power and water systems and the consequences of system interruptions caused by earthquakes. Additional study will be undertaken to further establish performance criteria that can be quantitatively mapped into the response space, in technological, economic, organizational, and social dimensions. Future study will also include the development of probabilistic procedures to estimate the reliability of the seismic resilience of the community. Also, integration with other critical systems such as emergency response organizations, medical care systems (a regionally designated network of acute care hospitals) and highway transportation systems will be carried out to evaluate community resilience. Finally, the application of SCADA in the inverse analysis of power system performance is of significant future interest. This is to improve the time it takes to achieve restoration of system function degraded by the earthquake, which is the rapidity aspect of the resilience criteria.

Acknowledgments

This research was primarily supported by the Earthquake Engineering Research Centers Program of the National Science Foundation, under award number EEC-9701471 to the Multidisciplinary Center for Earthquake Engineering Research. This support is gratefully acknowledged.
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