Simulating Earthquake Damage to the Electric-Power Infrastructure: A Case Study for Urban Planning and Policy Development

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Abstract

This paper presents a case study of the consequences of a Richter magnitude 6.75 earthquake on the Los Angeles Elysian Park fault to the electric-power infrastructure of the western United States. The analysis combines aspects of geological modeling of such an earthquake with probabilistic simulation of power-system component failures for evaluation of the operation of the engineering infrastructure. This hybrid analysis demonstrates emergent behavior of a complex system and illustrates the challenges of multi-disciplinary analyses necessary for computational operations research. The simulation predicts blackouts in the Los Angeles metropolitan area and abnormal voltages throughout the western U.S. electric-power infrastructure that compare favorably with the consequences observed following a recent Northridge earthquake. The paper discusses applications of such analyses for urban planning and policy development.

1. INTRODUCTION

Assessment of the possible consequences of a major natural disaster is a daunting problem. This paper presents an approach to the assessment of the implications of a moderate earthquake in the Los Angeles basin to the electric-power infrastructure of the western United States. Such assessment requires evaluation of a complex system of systems, requiring expert knowledge of the operation and behavior of each system, the interactions between these systems. The assessment also must accommodate the tremendous uncertainties associated with the range of characteristics of such an earthquake and the possible states of operation of the electric-power infrastructure of the western United States associated with season of the year, time of day, and prices of electric-power markets. Nevertheless, the approach presented herein provides a glimpse into the interactions of this system of systems. This information may be useful in urban planning to mitigate the human consequences of such a disaster; in engineering for the electric-power infrastructure to design transmission circuits, site generation resources, and operate the system with appropriate resource reserves; and in disaster response to anticipate likely resource requirements and prepare contingencies for efficient infrastructure restoration.

Interest in the ability to make such assessments has increased considerably in the past decade. This interest is due in part to the International Decade for Natural Disaster Reduction (IDNDR). The efforts have included combining expertise across diverse disciplines to evaluate disasters as systems of systems, leveraging increases in the capabilities of computer simulations and advances in modeling the security of our urban and national infrastructures. Another aspect of this effort has increased the focus on problems of disasters in large cities. For instance, the United Nations (United Nations Center for Human Settlements, 1996) estimates that by the year 2025, 61% of the world's population will be living in cities and there will be 28 "giant metropolitan complexes" of over 8 million people. Another study (Degg, 1992) showed that 78% of the world's 100 most populous cities are exposed to earthquakes, tsunamis, volcanoes, or windstorm, with 45% exposed to more than one such hazard.

Disasters in large cities pose an enormous risk not only to the city itself, but to the hinterland and national economy of the country as well. This risk is propagated directly by the energy, communication, and transportation infrastructures serve the city, and indirectly through resource allocation during the response to the disaster. Evaluating such disaster consequences has been the focus of projects such as RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas Against Seismic Disasters) (Tucker, 2001), Earthquake and Megacities Initiative sponsored by the IDNDR (Green, 2001), and the Urban Security Initiative (Heiken, 2000). In a large city, the high population density, complex societal mix, large income gap, abject poverty, and a large informal sector lead to a complex intermingling of cause and effect which is only compounded by the increased reliance on technological systems for normal functioning. Thus recovery can be slow in such cities owing to the greater vulnerability of infrastructure networks or what may be termed the lifelines of the city (Mitchell, 1995). The concentrated but distributed functionalities such as food, power, transportation, etc. all depend on high-tech infrastructure that breaks down at the time of a disaster and paralyzes the city. An important aspect of addressing the problems of disasters in large cities is to understand better the performance of the various urban systems such as transportation, electrical generation-and-distribution, housing, water supply, and so on and the inter-linkages between them (Maheshwari, 1999). These factors have led to the focus on integrated modeling (combining methods from various disciplines into a comprehensive analysis) that is presented in this paper.

This paper summarizes a research effort at the Los Alamos National Laboratory (LANL) assessing the potential impact to the national electric-power infrastructure from earthquakes. It presents a context for this work, discusses geological and engineering aspects of the problem, and presents results of a simulation of a moderate earthquake on Los Angeles' Elysian Park fault and the possible consequences of such an event. Finally, this paper discusses operations-research applications of the work for urban planning and disaster mitigation.

2. RESEARCH CONTEXT

Modern urban centers depend on infrastructure systems such as transportation, communication, electric power and energy, water and sewage system, etc. The electric-power infrastructure (EPI) is particularly important to a wide range of activities, including lighting, heating, ventilation, air conditioning, refrigeration, residential and commercial appliances, communication, vehicular and air traffic control, control systems, and various commercial and industrial processes. The loss of electricity due to an earthquake can cost billions of dollars to a national economy. The EPI is vulnerable to earthquake damage, as was observed in earthquakes at Loma Prieta and Northridge in California and at the Anatolian fault in Turkey.

The operation of the electric-power transmission system can propagate damage from the geographical location of the earthquake to other locations throughout the grid. For example, although physical damage to electrical components due to the Northridge Earthquake was restricted to locations in Los Angeles, this damage caused power outages as far away as British Columbia, Montana, Wyoming, Idaho, Oregon, and Washington (the longest outage lasting 3 hours in southern Idaho) (Schiff, 1995). Therefore, when evaluating possible consequences of earthquakes and other disasters to an EPI the approach must include both the vulnerability of individual components to the first-order consequences of the disaster and the evaluation of the operation of the remainder of the infrastructure with the loss of these components. Such an approach will enable us understanding how, for example, an earthquake in Los Angeles will affect regions far beyond the Los Angeles metropolitan area. To evaluate the system performance of the EPI following a scenario earthquake, there are at least three models to be integrated:

1) modeling the mechanics of ground motion through parameters such as peak ground acceleration, peak ground displacement, and ground-motion spectral energy for the scenario earthquake,
2) combining the predicted ground motion with individual-component fragility to calculate a damage state for each power-system components, and
3) using the damage-state probabilities to undertake systems-engineering analysis to evaluate the performance of the electrical system.

Although models for each of these aspects of the systems problem have been developed and used independently, integrating these models into a comprehensive analysis is a novel aspect of this research. The objective of this paper is to understand this integrated approach to modeling and to present the results of an example of this approach in the context of a moderate earthquake of Richter magnitude 6.75 at the Elysian Park fault under downtown Los Angeles. The paper will discuss the existing methods, problems related to data, and new methods used in each of the above models for this paper. Finally, the paper will provide results of the tests of the above approach for the City of Los Angeles and discuss briefly the policy implications of such modeling and how results of such integrated models can be useful to decision makers.

3. EARTHQUAKE AND INFRASTRUCTURE SIMULATION

3.1 Modeling Scenario Earthquake Ground Motions

One of the most important aspects of understanding the effects of an earthquake is to predict with a high degree of reliability the resultant ground motions. The distribution of ground motion in real earthquakes is often very non-uniform and consequently the distribution of damage is also non-uniform. This was seen in the Loma Prieta earthquake in California and again in the Northridge earthquake in Los Angeles. The three-dimensional nature of the velocity structure in deep sedimentary basins makes it very difficult to predict the ground motions in Los Angeles (Olsen and Archuleta, 1996). Most ground motion studies have been limited to a one-dimensional velocity model using the method of propagating ruptures on a finite fault and do not incorporate the effects of basin structure. More recently efforts have been made to develop more complicated 2D or 3D velocity structures. Although most such efforts limit the earthquake source to be a point source or a plane wave, some recent efforts include the modeling of a 3D velocity structure and a propagating rupture on a finite fault area (Olsen and Archuleta, 1996). The Olsen-Archuleta method was used in this study. It utilizes first-principle simulations of the earthquake ground motions and takes into account subsurface geology, particularly in basin structures. It also includes important effects of surface sediments. Although some studies are limited to low frequencies (less than 1 Hz), the ground motions used in this study incorporate high frequencies (as high as 3 Hz). This was considered essential because ground motions with significant energy content at frequencies of 3 Hz and greater cause damage to the components of the various urban infrastructure systems. The finite area that was modeled using this method incorporated a grid mesh of 75 x 75 nodes at regular spacing 2 km apart, covering the Greater Los Angeles area.

The method was validated against the Northridge earthquake and the results obtained compared favorably to the ground motions measured during the Northridge earthquake, as shown in Figure 1. Furthermore, the ground motions produced by this model were a better description of the measured ground motions than were the ground motions produced by HAZUS™ (National Institute of Building Sciences, 1997), as shown in Figure 2. The event for this simulation was an earthquake of Richter magnitude 6.75 at the Elysian Park fault. This fault is below downtown Los Angeles. The Elysian Park fault is a member of the Los Angeles Fault System (Olsen and Archuleta, 1996). The Los Angeles Fault System has a collective average recurrence interval for a Richter magnitude 7.2 to 7.5 earthquake that is similar to that of the San Andreas fault. An earthquake on the Elysian Park fault can be significant for the City of Los Angeles because of its proximity to the center of that city. The estimated ground motion (peak ground acceleration) for the scenario earthquake is shown in Figure 3.

3.2 Electrical Network Component Fragility

Fragility curves are used to estimate the probability of a certain level of damage to the equipment based on ground motion parameters at the site of the equipment (Anagnos, 1998). These curves are developed from data from past earthquakes to determine the probability that a certain level of damage is likely to occur to a certain type of equipment/structure based on the ground motions experienced at the site. An example of a fragility curve is shown in Figure 4. Each fragility curve is characterized by median and lognormal standard deviation values of the ground-motion parameter. For the analysis of electrical systems, the ground-motion parameter commonly used is peak ground acceleration. The Utilities Working Group (UWG) is a group of experts from several California utilities that convened in 1993 to assess earthquake-damage data and that developed standardized classification of electrical equipment. For each of the equipment classes, the UWG defined failure modes and developed opinion-based fragility curves, and other studies are ongoing to compare these fragility curves with real damage data to analyze the validity of the opinion-based fragility curves (Anagnos, 1998). However, the development of fragility curves based on damage data alone is difficult as most often damage data are insufficient to adequately define a fragility curve. Other methods such as HAZUS™ use fragility curves based on a combination of expert-based fragility curves and damage data from various earthquakes (National Institute of Building Sciences, 1997). Even though the use of fragility curves has limitations of generality, it was considered appropriate for this research.

For electrical substations and networks, the HAZUS™ method (National Institute of Building Sciences, 1997) classifies electrical network components in three broad classifications – substations, distribution circuits, and generation plants. Each class is further subdivided into subclasses depending upon criteria such as high-, medium-, and low-voltage substations with anchored and unanchored components (Table 1). For each classification, fragility curves are developed based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents (National Institute of Building Sciences, 1997). For example, a electric-power substation will have a state of extensive damage when there are failures of 70% of its disconnect switches, 70% of its circuit breakers, 70% of its current transformers, or 70% of its transformers. Each damage states is described in detail in Table 2.

Ground-motion data from the Olsen-Archuleta model (section 3.1) were combined with electrical-substations and generation-plant data (section 3.3) and were processed using the fragility-curve models of HAZUS™. The results of this calculation were damage-state probabilities for each substation and generating station. These probabilities were used in a Monte Carlo procedure that calculated a specific damage state for each component as described in section 3.3.3.

3.3 Engineering Analysis

The EPI is a collection of generating plants that produce electrical energy by converting other energy resources, a network of high-voltage transmission lines that convey electricity from the generating plants to substations where the voltage is lowered by transformers, and a subordinate collection of radial distribution networks that deliver low-voltage electric power to end-use consumers (Rustebakke, 1983). The U.S. EPI contains generating plants that harness coal, natural-gas, nuclear, and hydro resources, as well as other energy resources including wind, solar radiation, and waste heat from industrial processes. The U.S. EPI's high-voltage transmission system is an alternating-current (AC) system divided into several standard nominal voltages, primarily 765, 500, 345, 230, 161, 138, and 115 kV. Higher-voltage transmission lines require less current per unit of power transmitted, thus lowering resistive transmission losses and improving efficiency. Transformers are sets of coils magnetically coupled on iron cores that interconnect the AC voltage layers. The transformers also can be controlled within limits to adjust the voltages at substations to the desired nominal values. Transformers also lower the voltages to practical levels for use by consumers.

The EPI of the continental U.S. is divided electrically into four interconnections – Western Systems Coordinating Council, the Eastern Interconnection, the Electric Reliability Council of Texas, and Hydro Quebec. Within each of the four interconnections, the sinusoidal frequency is controlled to a nominal 60 Hz. All generating units within an interconnection produce electricity with the same frequency, regulated to within 0.00014 Hz average error each hour (NERC, 1995). The stability of the control of these generating units' speeds is an important reason for the partitioning of the EPI into independent interconnections. The AC transmission systems of the four interconnections are connected by a small number of AC-DC-AC converter stations that provided limited power transmission between the interconnections (Hauth, 1996).

The interconnection containing Los Angeles is the Western Systems Coordinating Council (WSCC). WSCC serves the western United States, western Canada, and a small portion of the Mexican states of Sonora and Baja California. In 1997, WSCC included 157,783 MW of generating capacity, served 65 million people across 1.8 million square miles, and contained 107 commercial utilities and independent power producers (WSCC, 2001). The WSCC EPI contained a transmission system with 89,077 miles of high-voltage transmission lines. It also contained three high-voltage DC transmission lines. These unusual components are useful for transmitting large amounts of power long distances. Two of the DC lines traverse California, bringing power to northern Los Angeles from the Oregon border. The third DC line crosses Nevada, bringing power to northeastern Los Angeles from west central Utah.

The importance of Los Angeles as a center for electricity utilization in WSCC should be emphasized. Data from the California Independent System Operator (CaISO) predicted a coincidental 1999 summer peak load for WSCC of 127,700 MW. Two utilities, the Los Angeles Department of Water and Power (LADWP) and Southern California Edison, serve Los Angeles and the surrounding urban and suburban region. These two utilities comprise 23,250 MW

(18.2%) of the CaISO summer-peak-load data. Public sources of information for these utilities can be found at the Federal Energy Regulatory Commission.

Traditional analyses of electric-power transmission systems emphasize calculations of the flow of power through a network of transmission lines (Grainger and Stevenson, 1994). Each node in the transmission network is characterized by two parameters of a phasor voltage, the magnitude and relative phase angle of this voltage. Each transmission line can be described by a pi-network equivalent, consisting of a series resistance and inductive reactance between the endpoints of the line, with a shunt charging capacitance between each of the endpoints and ground. This characterization leads to a large system of nonlinear equations. (Tinney and Hart, 1967) proposed a technique for the efficient solution of this system of equations, and their technique is still used in commercial engineering software. In most transmission lines the line impedance is dominated by the series inductive reactance, and this characteristic can be used to linearize the system of equations for an efficient approximate solution (Wood and Wollenberg, 1984). Power-flow analyses for this study used a nonlinear solution code developed by the University of Texas at Arlington's Energy Systems Research Center.

3.3.1 Data Requirements

The power-flow calculations require specification of engineering parameters for individual substation-bus, transmission-line, and generating-unit components. Generating-unit data include the scheduled real-power output from the generator, the maximum and minimum reactive-power limits for this scheduled real power for voltage control, and the desired generator-bus voltage for adjustment of reactive-power generation. Transmission-line data include the two substation buses linked by the line, the pi-network impedance (series resistance, series reactance, and shunt capacitance), and MVA power-flow capacity. If the line is a transformer, then the voltage-adjustment tap setting and any phase-angle regulation are also required. Substation-bus data include the aggregate real and reactive power for the consumers served from the bus, and any shunt compensation used for voltage control.

EPI data for this study came from several sources. The CaISO provided engineering data for this study. The CaISO summer coincidental peak-load database includes data for 9999 substation buses and 12727 transmission lines, representing all of WSCC. These data include all parameters necessary for power-flow calculation, including a consumer-load forecast and a schedule of generating-unit commitment. The California Energy Commission and the Federal Energy Regulatory Commission provided transmission-system maps of California and Los Angeles.

3.3.2 Integration Challenges

Coupling analyses of the geology of ground motions of earthquakes and consequential analyses of probabilistic failures of infrastructure components with the engineering analyses of the power flow through the EPI presents several novel challenges. One of the most interesting of these challenges is the identification of geographical areas served by the (radial) distribution systems emanating from EPI transmission substations. Individual substations serve a distribution network that provides electric power to consumers in a specific geographic area. This area is called the substation's service area. Although this area is known precisely to the utility that owns the substation, the area is not documented by public regulatory agencies. Ergo, the area must be estimated by non-utility organizations performing geographic-based (e.g., urban-planning) studies. This problem has been examined previously using Voronoi estimation techniques (Newton and Schirmer, 1997), but that approach has deficiencies in ability to use population-density and land-use data to improve service-area estimates or to avoid water and rough-terrain obstacles that present service-area constraints. Los Alamos National Laboratory (LANL) has explored a cellular-automata service-area estimation technique for improved use of geographic data (Fenwick and Dowell, 1999) and with application to load-forecasting using synthetic-population methods (Dowell, 1999).

Another important challenge is the coupling of the probabilistic failure states of substations computed by HAZUS™ to a scenario of failures specific to discrete components represented in the EPI database. This challenge can be overcome using a Monte Carlo technique. Using a good random number generator (L'Ecuyer, 1988), a failure state for each component is selected from the range of failure states using the HAZUS™ failure-state probabilities as a mathematical mapping function. Then the component failures are reported to the EPI database for subsequent evaluation of consequences to power flow through the components that survived the earthquake. This Monte Carlo procedure can be repeated to generate a probabilistic prediction of EPI transmission or voltage problems, or the similar likelihood of blackout for specific geographic locations.

A significant uncertainty in the assessment of post-earthquake consequences of EPI power-flow conditions is the range of human and machine events that will occur following a stress to the EPI. Specifically, the greater loss of load relative to loss of generation capacity anticipated from an earthquake in the Los Angeles area will leave WSCC with a surplus of scheduled generation. To control voltages and to maintain 60-Hz system frequency, automatic and manual choices will be made to turn off generation across WSCC. These choices involve decisions by human operators at utility and independent-system-operator control centers, and the range of choices makes prediction of the decisions difficult. Even the actions of the automatic generation control systems are difficult to predict, owing the proprietary nature of these control systems, the variations in policies for load shedding and voltage control among the several utilities of the WSCC, and the complex and temporally-dependent nature of these systems.

Finally, an objective of the analyses of the implications of earthquakes to the EPI is the evaluation of policies for urban planning, infrastructure development, resource allocation, and infrastructure restoration. However, the output from the EPI engineering analyses is a prediction of the electrical state of the various EPI components. Coupling these engineering analyses with policy decisions is an important challenge. Although outwardly unrelated, EPI calculations can reveal information useful for selecting policies. Specifically, the identification of likely infrastructure failures is useful for determining the type and quantity of spare parts needed for infrastructure restoration. The expected quantity and cost of these spare parts, and decisions about desirable locations for their storage, can be determined from analyses of EPI damage from earthquakes. Likewise, such analyses can assist in planning for emergency generators in essential facilities in areas that are likely to experience blackouts. Such analyses can help decision makers decide where emergency generators or other power supply is needed and for how long.

3.3.3 Simulation Methods

The procedure for EPI analyses in this study is to couple the results of the HAZUS™ analyses to the EPI database, perform base-case and post-earthquake power-flow studies, and present the results in geographic information system (GIS) and tabular formats.

A damage scenario is produced from the HAZUS™ results by selecting a damage state for each EPI substation using a Monte Carlo technique. The HAZUS™ results report the percentile probability that the damage state will be no damage, slight damage, moderate damage, extensive damage, or complete damage. The percentages for each state comprise a partition of the real-number space between 0 and 1. A uniformly-distributed random number between 0 and 1 (L'Ecuyer, 1988) selects a state for each substation from the possibilities, and this state is used for the subsequent EPI analyses. With no damage, no modification is made to the substation in the EPI database. For complete damage, the substation is removed from the database, and any generating units or transmission lines connecting to this substation become disconnected and so are removed from the database. Similarly, extensive damage (independent 70% probability of failure of each circuit breaker, switchgear, bus component, transformer, etc.), results in a likelihood of less than 0.07% that each transmission circuit terminating at the substation will remain operable. Substations having extensive damage were removed from the database, along with the incident generating units and transmission lines. For substations with slight or moderate damage, the substation was left in service in the database, with a reduction in the aggregate consumer load resulting from probable failures of portions of the substation's distribution apparatus.

The EPI analyses determine the power flow through each transmission line and the voltage at each substation node. An analysis was performed for the base case (pre-earthquake condition under the assumptions of the CaISO data set) and for post-earthquake conditions for a single Monte Carlo scenario sampled from the HAZUS™ analysis of an Elysian Park earthquake. Differences between the results of these two analyses indicate consequences of the earthquake.

GIS presentation of the results was made possible by geographic information obtained from maps from the California Energy Commission and the Federal Energy Regulatory Commission. These maps were scanned and registered for display by commercial GIS software, with overlays digitized from the maps to indicate the locations of EPI components found in the CaISO database. The digitized GIS objects allow a graphical presentation of the results of the EPI analyses.

The digitized substation locations were superimposed on a GIS database of Anderson land-use codes for geographic subregions throughout the Los Angeles study area. LANL cellular-automata software estimated the service areas of each substation in the study area using this graphical presentation. The resulting bitmap image allowed additional graphical presentation of the consequences of the earthquake.

4. SIMULATION RESULTS

Figure 5 shows the estimated service areas of substations in the Los Angeles study area. Each area represents geographically the set of consumers expected to be served by each of the substations. Some remote agricultural and forest terrain northeast of Los Angeles was excluded from the estimate owing the large uncertainty in the identification of the substation(s) serving this region. Because of the small consumer load of this region, impact of this uncertainty to our analyses was negligible.

Table 3 shows the results of the HAZUS™ damage-state probability calculation and the result of a single Monte Carlo sample of damage states for representative substations in the study area. Substation damage ranged from none to complete. As can be expected from Monte Carlo simulation, some low-probability results were selected. The HAZUS™ results found 43 substations with a probability of extreme or complete damage exceeding 50%. These substations and substations and their Monte Carlo-selected scenario damage states are listed in Table 4.

Figure 6 shows the Monte Carlo-selected scenario damage states for each substation in the Los Angeles study area. Note the geographic correlation between the substations experiencing complete failure with the location of the Elysian Park fault.

Figure 7 shows areas of Los Angeles where blackout occurs from consequences of the earthquake. This figure shows areas where blackout occurs either from first-order isolation resulting from the failure of a substation cutting off the flow of power to the distribution system, or from second-order isolation by substation failures removing all transmission paths to substations downstream. Blackout will occur at substations experiencing second-order isolation because no transmission circuits remain to bring power to these substations, even though no earthquake damage occurred at the substation. Using data from the CaISO 1999 summer-peak-load database, the first- and second-order isolation removes 11,448 MW of consumers' loads and 4,400 MW of scheduled generation from the EPI. The load removed by the Elysian Park earthquake scenario is 8.9% of the entire WSCC EPI load. The removed scheduled generation is 3.3% of the entire WSCC EPI generation. These perturbations leave WSCC with a significant excess of scheduled generation. This excess generation will produce higher-than-nominal voltages and increased system frequency. Manual and automatic generation control must reduce the generation to match the post-earthquake load to prevent these voltage and frequency problems.

As a basis for comparison, we reduced the surviving scheduled generation uniformly (to 95% of the scheduled value) across WSCC. This reduction in generation matched closely the post-earthquake demand (plus transmission losses resulting from the new generation schedule). The consequent power flow revealed several problems for the WSCC EPI. Two types of problems occur. First, power flow is shifted by the line failures and changed load and generation schedules, producing thermal overloads (flows that exceed the thermal capacities of transmission lines). Overloads that occur are small (a few tens of megawatts on only eight transmission lines) and could be mitigated by changing the post-earthquake generation schedule. Second, the failures produce changes in reactive power flow that lead to non-nominal voltages at substations. These problems are more serious. There are 129 substations with voltages 10% or more above normal, and one substation with voltage 20% above normal. These are large excursions from the normal voltages, and could exceed the capability of the voltage-control apparatus to mitigate these abnormal voltages. These abnormal voltages occurred throughout WSCC. Table 5 lists the number of substations having abnormal voltages in each of the WSCC control-area subsystems, and Figure 8 shows the locations of these substations. Several of these substations' abnormal voltages are serious problems, particularly those at substations of the high-voltage backbone through northern California, Washington, and Oregon. Abnormal voltages occur at the Malin, Captain Jack, and Grizzly substations in Oregon; Hanford, Ashe, Lower Monumental, Little Goose, and Lower Granite substations in Washington; Round Mountain and Olinda substations in California; and at substations as far away as Colorado and British Colombia. More information is necessary to predict how the WSCC EPI's relays and other devices would respond to these abnormal voltages, to determine if there could be cascading failures that would result in blackouts of areas far removed from Los Angeles for this Elysian Park earthquake.

5. FUTURE RESEARCH

Several changes could improve this EPI analysis of the consequences of an Elysian Park earthquake. First, the HAZUS™ failure probabilities are assumed to be independent in the Monte Carlo scenario realization. In the Monte Carlo simulation, it is possible for adjacent buses at the same substation to experience radically different failure states. Modification of the HAZUS™ results to produce conditional probabilities for correlated failures at substations could reduce this effect. Also, the HAZUS™ results are aggregate for entire substations, but must be decomposed to produce failure states for individual substation buses and transmission-line switchgear. Modifying HAZUS™ to produce failure states for each of the components specific to the CaISO database would improve this facet of the analysis. Further, fragilities for transmission lines could produce HAZUS™ failure probabilities for those circuits that traverse the earthquake area with towers and other apparatus that could be affected by ground motion. Circuit routes could be determined from California Energy Commission maps to use such fragility data.

Second, the generation rescheduling determined to be necessary following an Elysian Park earthquake will require human decisions. The specific decisions determining which generators will be rescheduled will affect the resulting power flow. Better representation of these human decisions would improve the simulation and analysis, requiring collaboration with the industries that operate these components.

Third, the EPI analyses that can be performed evaluate pre- and post-earthquake steady-state conditions. However, the temporal aspect of the infrastructure during the failures is important. Voltage transients will occur as substations fail, generators become isolated, and circuit breakers disconnect transmission lines. The specific times of these events cannot be forecast, but the important transient EPI phenomena depend upon these times. Similarly, additional data are necessary to model the high-frequency behavior of generating units and control devices during transients, but these data are unavailable. Although transient phenomena are important during EPI catastrophes, they are difficult or impossible to model.

Finally, the EPI analyses for this study used the assumptions of the CaISO summer-peak-load forecast for WSCC. The pre- and post-earthquake conditions depend on the load and generation schedules from this assumption. The analyses could be improved by using the population and land-use databases in conjunction with the estimated substation service areas to predict off-peak loads to assess the consequences of Elysian Park earthquakes at arbitrary times.

6. APPLICATIONS TO URBAN PLANNING

The results of analyses of earthquake implications to the electric-power infrastructure can provide information valuable for urban planning and disaster mitigation. Ideally, the data produced could be used to improve the design of the infrastructure, by changing the routing of certain transmission corridors into affected neighborhoods to reduce the likelihood that all transmission paths would be damaged by the disaster. However, the cost and social barriers to such major construction of overhead transmission lines are likely to preclude such measures. Instead, the data can be used to site replacement equipment and supplies, to forecast the extent of blackout areas and their consequences, and to plan restoration procedures.

Repair and replacement of damaged apparatus is essential to the restoration of power following an earthquake-induced blackout. The fragility data indicate the possibility of damage to transmission-line towers; substations' circuit breakers, transformers, and switchgear; and communications apparatus. Certainly, preparing a stock of repair and replacement parts for this equipment is important. Also important is the standardization (to the extent possible) of this equipment, so that the repair and replacement parts will avail the most general application. The forecast of damage from the simulation can be used to determine what types and how many of the spare parts should be stocked. A final consideration is the location of these parts, in areas that are possibly sheltered from potential damage using means that further protect these parts from damage, in physical locations that will be accessible to repair crews, proximal to locations where damage is likely, and where transportation infrastructure surviving the earthquake will be available for the transport of these parts to where they are needed.

The forecast of the blackout area is an important result of the simulation. These data can be used to determine the consequences of the earthquake to the services that depend on electric power. Such services include medical facilities, food storage, and communications. The data can be used by disaster-relief agencies to determine the number of persons likely to be affected, the quantities of survival and medical supplies needed, and the duration for which important services may be affected.

A final application of the forecast of the blackout area is the development of plans to restore power. Prioritization of the repair of transmission routes bringing power into the affected neighborhoods is possible. By concentrating restoration efforts on the minimal critical transmission paths needed to bring restore power to the affected neighborhoods, the duration of the blackout can be reduced.

Although it is likely impossible to design the electric-power infrastructure so that it is invulnerable to damage from earthquakes, integrated analyses of earthquake ground motions and their consequences to infrastructure operation can mitigate these consequences. As the urban populations in locations vulnerable to natural disasters continue to grow, awareness and preparedness will become increasingly important to limit the consequences of these disasters to human life and welfare.

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Figure Captions

1. The earthquake model used in this paper compares favorably with earthquake measurements. Here are the modeled peak ground accelerations (left) and measurements (right) for the recent Northridge earthquake. The model was accurate in both the magnitude and geographic extent for this event.

2. A HAZUS™ model (left) of the recent Northridge earthquake underestimated the peak ground acceleration and overestimated the geographic extent of the event. This figures compares this model with the measurements (right).

3. The model used in this paper predicts peak ground accelerations as high as 1.02 g for a 6.75 Richter magnitude Elysian Park earthquake. This is the scenario explored in this paper.

4. Component fragility curves show the probability of various damage states for an electric-power substation as functions of peak ground acceleration during an earthquake.

5. A cellular-automata technique used land-use data and electric-power substation locations to estimate substations' service areas.

6. Damage states for substations affected by the earthquake were simulated with Monte Carlo techniques using the component fragility curves and the predicted peak ground accelerations. This result for a single iteration of the Monte Carlo simulation shows the correlation of expected substation failure with proximity to the Elysian Park fault.

7. Substation failures can cause blackouts in their service areas, and can cause blackouts in the service areas of neighboring substations that become isolated by other failures that cut off paths of power flow through the transmission grid.

8. The modeled Elysian Park scenario produced abnormal voltages at substations throughout WSCC. This phenomenon also was observed following the recent Northridge earthquake.

Table 1
Classification of Electrical Network Components as used by HAZUS™ Source: HAZUS™ (FEMA 1997)

Name	Description
	Transmission Substations
ESS1	Low-Voltage (less than or equal to 115 kV) Substation with Anchored Components
ESS2	Low-Voltage (less than or equal to 115 kV) Substation with Unanchored Components
ESS3	Medium-Voltage (115 kV - 230 kV) Substation with Anchored Components
ESS4	Medium-Voltage (115 kV - 230 kV) Substation with Unanchored Components
ESS5	High-Voltage (230 kV - 500 kV) Substation with Anchored Components
ESS6	High-Voltage (230 kV - 500 kV) Substation with Unanchored Components
	Distribution Circuits
EDC1	Distribution Circuits with Seismically Designed Components
EDC2	Distribution Circuits with Standard Components
	Generation Plants
EPP1	Small Power Plants with Anchored Components < 100 MW
EPP2	Small Power Plants with Unanchored Components < 100 MW
EPP3	Medium/Large Power Plants with Anchored Components ≥ 100 MW
EPP4	Medium/Large Power Plants with Unanchored Components ≥ 100 MW

Table 2
Description of Various Damage States for Electrical Network Components (Source: HAZUS™, FEMA 1997)

Damage State Description	**Substations**	**Distribution Circuits**	**Generation Plants**
Slight/Minor	Failure of 5% of the disconnect switches, 5% of circuit breakers, or by building being in minor damage state	Failure of 4% of all circuits	Turbine tripping, light damage to diesel generator, or building being in minor damage state
Moderate	Failure of 40% of disconnect switches, 40% of circuit breakers, 40% of current transformers, or building being in moderate damage state	Failure of 12% of all circuits	Chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or building being in moderate damage state
Extensive	Failure of 70% of disconnect switches, 70% of circuit breakers, 70% of current transformers, 70% of transformers, or building being in extensive damage state	Failure of 50% of all circuits	Considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or building being in extensive damage state
Complete	Failure of all disconnect switches, all circuit breakers, all transformers, all current transformers, or building being in complete damage state	Failure of 80% of all circuits	Extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or building being in complete damage state

Table 3

HAZUS™ Component Damage-State Examples. This table lists substation names, probabilities that each one of the five different damage states will occur, and the Monte Carlo selected damage state for the Elysian Park earthquake scenario

Name	None	Slgt	Mod	Ext	Comp	Result
A	3%	4%	13%	64%	16%	Complete
Center	0%	0%	1%	36%	62%	Complete
F	1%	1%	4%	55%	39%	Complete
Mesa	1%	1%	3%	50%	46%	Complete
Rio Hondo	5%	15%	28%	47%	5%	Complete
Serrano	4%	7%	12%	70%	7%	Complete
B	3%	10%	21%	56%	10%	Extensive
Barre	3%	10%	21%	56%	10%	Extensive
Center	1%	3%	7%	53%	36%	Extensive
D	7%	18%	31%	41%	3%	Extensive
Del Amo	7%	18%	31%	41%	3%	Extensive
E	4%	7%	12%	70%	7%	Extensive
C	9%	22%	33%	34%	2%	Moderate
Cimgen	22%	36%	31%	11%	0%	Moderate
E	22%	36%	31%	11%	0%	Moderate
Eagle Rock	12%	15%	33%	39%	2%	Moderate
El Segundo	1%	18%	56%	20%	5%	Moderate
Ellis	9%	11%	28%	49%	4%	Moderate
Del Amo	5%	5%	18%	62%	11%	Slight
El Segundo	2%	24%	57%	15%	3%	Slight
Elizabeth Lake	72%	25%	3%	0%	0%	Slight
Estrero	90%	9%	0%	0%	0%	Slight
Q	12%	26%	35%	26%	1%	Slight
San Fernando	29%	40%	25%	6%	0%	Slight
Castaic	80%	19%	0%	0%	0%	None
Gould	29%	40%	25%	6%	0%	None
Rinaldi	50%	32%	17%	2%	0%	None
Santa Susana	90%	9%	0%	0%	0%	None
Santiago	54%	37%	9%	0%	0%	None
Santicoy	72%	25%	3%	0%	0%	None

Table 4.
Substations with Greatest Probability of Failure. Substations having probability of damage exceeding extreme greater than 50%, with the selected Monte Carlo damage state for the study scenario.

Name	Probability that Damage Exceeds Extensive	Result
P	100%	Ext
Center	98%	Comp
Laguna Bell	97%	Comp
Mesa	96%	Comp
F	94%	Comp
Coldgen	91%	Comp
Center	89%	Ext
Lighthipe	89%	Ext
Barre	89%	Ext
River	89%	Ext
Walnut	85%	Ext
Laguna Bell	84%	Ext
Refuse	80%	Comp
Growgen	80%	Comp
Mesa	80%	Ext
A	80%	Comp
Lewis	80%	Slgt
Rio Hondo	80%	None
E	77%	Ext
Serrano	77%	Comp
Pumpgen	76%	Ext
G	73%	Ext
Hinson	73%	Ext
Del Amo	73%	Slgt
B	66%	Ext
Barre	66%	Ext
Lighthipe	66%	Ext
Airway	64%	Comp
La Cienega	64%	Ext
La Fresa	64%	Mod
El Nido	64%	Ext
Arcogen	64%	Ext
Harborgen	64%	Comp
Olinda	64%	Ext
Villa Park	64%	Ext
Gramercy	59%	Mod
Hillgen	59%	Mod
Walnut	59%	Ext
H	53%	Ext
Johanna	53%	Ext
Goodrich	53%	Ext
Ellis	53%	Mod
Rio Hondo	52%	Comp

Table 5
Post-Earthquake Abnormal Voltages. WSCC control zones having post-earthquake substation voltages 10% or greater than normal, and number of substations with these abnormal voltages.

Control Zone	Number of Abnormal Voltages
Arizona	1
PG&E	14
Northwest	94
B.C. Hydro	4
W. Kootenay	1
Idaho	3
Montana	2
Sierra	3
PACE	3
WAPA L.M.	2
WAPA U.C.	1