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POST-EARTHQUAKE RESTORATION MODELING OF ELECTRIC POWER SYSTEMS

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SUMMARY

The time it takes to restore lifeline services is a critical determinant of a community's ability to recover after an earthquake. This paper describes a new, discrete event simulation approach to modeling the post-earthquake restoration process for electric power systems. It begins with a discussion of past restoration modeling approaches, summarizing advantages and disadvantages of each. The new simulation modeling approach, which could be applied to any lifeline system, is presented, followed by a description of how it has been applied to the Los Angeles Department of Water and Power (LADWP) electric power system specifically. The paper concludes with summary remarks about the key innovations of the new method and plans for future work. This study is part of the MCEER LADWP demonstration project.

INTRODUCTION

Following an earthquake, loss of infrastructure system functionality can significantly disrupt normal economic activity. The duration of this loss of service is a critical determinant of the ultimate magnitude of economic disruption. It can especially affect, for example, business interruption and indirect economic loss. Quantitative models of the post-earthquake restoration process, therefore, are important in evaluating the total economic loss caused by an earthquake. The objective of this study is to develop an improved model of the post-earthquake electric power system restoration process. The discrete event simulation model uses estimates of initial physical damage to the system and an understanding of the repair and recovery operations to estimate geographically-disaggregated restoration curves, including uncertainty bounds on those curves.

This study is part of a Multidisciplinary Center for Earthquake Engineering Research (MCEER) effort to assess the economic and societal resilience of a community. In particular, this study is contributing to the MCEER Los Angeles Department of Water and Power (LADWP) demonstration project. Established in 1902, the LADWP is the largest municipal utility in United States. The Department has 1.4 million electric power customers, 640,000 water customers, and overall service area of 464 square miles (Figure

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1). MCEER's integrated earthquake loss estimation methodology for urban lifeline systems, first developed as part of the Memphis Light, Gas and Water Division (MLGW) demonstration project (Chang [1], [2], and [3]), is now being used in the LADWP project. That methodology, which evaluates direct and indirect economic losses from lifeline failures, enables assessment of both expected losses from future earthquakes and potential loss reduction from mitigation alternatives. It requires a restoration model that can update the damage state of the lifeline system at each time step from the time of the earthquake until the system is fully repaired. The restoration model presented in this paper aims to improve the one currently being used to update damage states at each time step.

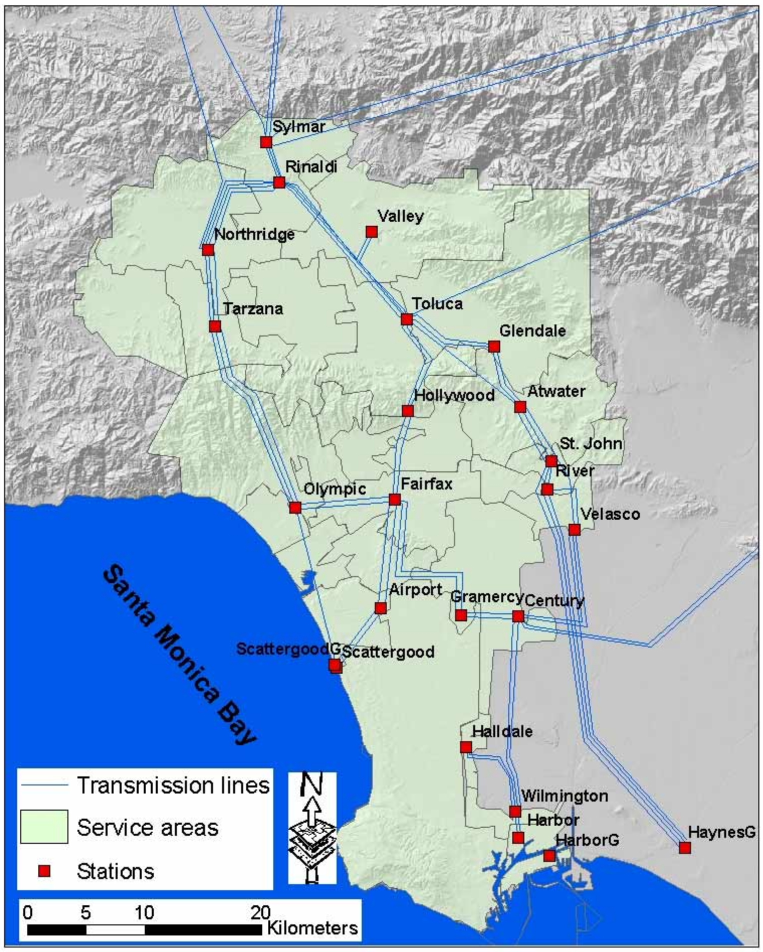

Figure 1. LADWP Electric Power Service Area (Adapted from Dong [4])

This paper begins with a summary of the literature on post-disaster restoration modeling for lifelines. The new discrete event simulation approach is then presented, followed by a discussion of a specific application of that approach to the LADWP electric system. The paper concludes with remarks about planned future work in this area.

PREVIOUS RESTORATION MODELING APPROACHES

Previous work in modeling post-earthquake lifeline restoration can be grouped into four main approaches: (1) statistical curve fitting, (2) deterministic resource constraint, (3) Markov process, and (4) network. The first two are empirically based; the second two are more theoretical. The first three focus on descriptively modeling the current restoration process; the last one is mainly used for developing optimum restoration strategies. The basic goal of all these approaches is to develop a curve or curves that represent the functionality of a lifeline system versus time. There are several key dimensions on which the models can be compared. It is desirable for a restoration model to:

- Include the utility company's decision variables explicitly, allowing exploration of their effects on the speed of the restoration. Possible decision variables include number of response personnel of different types, amount of repair materials of different types, and repair prioritization rules.
- Produce different restoration curves for each region within the service area rather than just one curve for the whole system. This facilitates modeling the economic impact of service interruptions.
- Represent the uncertainty in the restoration curve.
- Model the real-life restoration process explicitly, potentially offering insights into the restoration process that are generalizable to other situations.
- Limit the extent to which simplifying assumptions about the restoration process are required and to ensure that any assumptions made are reasonable.
- Require only available data.
- Be flexible so that it can be applied to other lifelines and hazards, and so that it can easily accommodate multi-lifeline interactions or changes in the restoration process or data.

The following sections describe each of the four approaches in turn, including discussion of the extent to which each exhibits these desirable characteristics.

STATISTICAL CURVE FITTING APPROACH

In the statistical curve fitting approach, data obtained from previous earthquakes and/or from expert opinion are employed to fit restoration curves. Either data are plotted and a restoration curve is fit to the data, or a functional form for the restoration curve is assumed and data are used to estimate the parameters for that function. This approach has been used in many previous studies, such as ATC-25-1 [5], Singhal [6], Chang [7], Shinozuka [8] and Nojima [9]. In ATC-25, restoration curves are constructed using ATC-13 [10] data sources that are based on regression analysis of expert opinion data obtained through an iterative questionnaire process. In Chang [7], restoration times for the water delivery system of the Memphis Light, Gas and Water Division (MLGW) were estimated using an empirical log-linear relationship between days of outage and break density. The days of outage-break density relationship was developed by Seligson [11] based on data from the 1971 San Fernando, California earthquake. Shinozuka [8] assumed an exponential function for the restoration curve for the electric power system of the MLGW. The parameters of this function were estimated using data from the Northridge earthquake and ATC-25. In Nojima [9], Gamma distributions were used as restoration curves. Parameters of the restoration curves were estimated as a function of the damage level using data from previous earthquakes. Nojima [9] allows one to spatially disaggregate the single "system restoration curve" into many restoration curves depending on seismic intensity.

In the statistical curve fitting approach, the restoration curves are derived from real data, but the actual restoration process is not modeled explicitly. The primary determinant of system restoration time is ground shaking intensity. Issues such as personnel and material constraints and opportunities to reduce losses by optimizing restoration are not considered (Chang [1]). Uncertainty and decision variables are not represented explicitly, and usually only one restoration curve is obtained for the entire lifeline system.

DETERMINISTIC RESOURCE CONSTRAINT APPROACH

In the deterministic resource constraint approach, the actual restoration process is modeled, but in a simplified way, typically using a set of simple equations and rules. Resource constraints are accounted for by specifying the number of repairs that can be made in any time period as a function of the number of repair personnel available. This approach allows depiction of the progress of the restoration across time and space, and enables investigation of the effect of some loss reduction efforts, such as, prioritizing spatial sequencing of repairs or using mutual aid agreements (Chang [1]). This approach has been employed in Isumi [12], Ballantyne [13], HAZUS—water supply system section (NIBS [14]) and Chang [3]. In Ballantyne [13], HAZUS, and Chang [3] the number of available repair personnel and rate of repair for various components of the system are assumed to be constant throughout the repair process. Repair rates are estimated using previous earthquake data and expert opinion. In the case of HAZUS and Chang [3], it has been further assumed that number of available repair personnel is a fixed percentage of the study region population. Using 1995 Kobe, Japan earthquake data, Chang [1] illustrated that these assumptions do not necessarily reflect what happens in reality. In Isumi [12], the restoration process in each service area is described by a differential equation, and the number of available repair personnel and rate of repair for various components are allowed to change with time. Isumi [12] also considers delays due to traffic and repair personnel shifts.

In these studies, the restoration process is modeled and resource constraints are considered, but the process is represented in a simplified way that assumes, for example, that restoration involves only repair, not damage assessment or other tasks. The models are deterministic, so the uncertainty associated with expected restoration time is not estimated.

MARKOV PROCESS APPROACH

Hoshiya [15], Noda [16], Yamada [17], Isoyama [18], and Iwata [19] model individual lifeline's functional performance in the post-earthquake period using discrete-state, discrete-transition Markov processes. In later studies, such as, Kozin [20] and Zhang [21] a discrete-state, discrete-transition Markov process is employed to model the evolution of the restoration of various lifelines together as a system. In Kozin [20] and Zhang [21], each lifeline is a subsystem of the overall urban system, and the subsystems compete for the limited restoration resources. Limited restoration resources are distributed optimally by making use of an immediate economic return vector. In Zhang [21], a straightforward approach is proposed to take into account the effects of interactions between various lifelines.

In the Markov process approach, the states of each subsystem at any stage of the restoration are considered to follow random processes. The present state may depend on the state in the previous time step, but is independent of other previous states. The transition probability matrix is defined such that each element p_{nij} is the probability that subsystem n will go from state i to state j in one time step. The probabilities in the transition probability matrix depend on the amount of restoration resources allocated for each subsystem at various stages of the restoration process. In Zhang [21], the effects of interactions are incorporated by considering the transition probability of each subsystem as a function of not only the allocated resource, but also the states of other subsystems.

This modeling approach can produce spatially disaggregated restoration curves, and can include decision variables and uncertainty explicitly. Its main disadvantage is that it requires data in the form of transition probabilities and state vectors, which can be difficult to obtain. Furthermore, the approach requires many simplifying assumptions about the system and the restoration process. For example, the assumption made in Zhang [21] and Kozin [20] that lifelines compete with each other for available restoration resources is not typically true in reality.

NETWORK APPROACH

In the network approach, each lifeline system and subsystem is assumed to consist of a supply node and a number of demand nodes. These are connected to each other via links that can be either damaged or fully functional. In Nojima [22], Minimum Spanning tree and Shortest Path tree structures that are extracted from the original network configuration are used for selecting a prioritized set of components to be repaired for recovery of network connectivity. Then Horn's algorithm (Horn [23]) is employed to determine the optimum repair sequencing for the damaged components included in the tree structure. This study combines graph theory and optimization theory to develop an optimal restoration plan. In Okumura [24], an alternative optimal repair sequencing method is proposed. That approach is based on the connectivity of a tree-shaped network and involves simplified flow analysis of the network as an approximate global optimization strategy. Results indicated that for networks with no loops, this approximate approach gives the optimal repair sequencing. Kameda [25] included the socio-psychological dimension of the problem in addition to the engineering dimension. He developed a methodology in which global optimization techniques are applied based on a curve of customer acceptance (of service level) versus time, rather than a typical curve of loss of functionality versus time. The customer acceptance versus time curve is constructed by combining (1) customer acceptance versus time curves for various service levels and (2) percent of functionality versus time curves for the same service levels.

Hoshiya [26] modeled the post-earthquake restoration of a water supply system in Tokyo using the network approach. In that study, water conveyance pipes and the main distribution pipes are modeled as links. Distributing reservoirs and pumps are modeled as nodes to which subsystems made up of distribution pipes of small diameter pipes are connected. Damage is assumed to be Poisson-distributed along each link. The restoration of each link is also assumed to follow a Poisson process with a constant restoration rate that depends on link properties, the number of damaged locations along the link, and the number of repair workers assigned for the link repair. Two strategies were employed in this study to distribute available repair personnel. In the first approach, restoration takes place from the source outwards along each source-demand series system. In the second approach, the optimal number of workers is assigned to each link such that all links are restored simultaneously. Repair sequencing strategies used in this study include: Minimum Spanning tree and Shortest Path tree approaches, and an approach based on choosing a link connected to an already restored node at each stage of restoration, such that service is restored to the maximum number of customers within the shortest time.

The network approach enables both spatial and temporal disaggregation of restoration processes and consideration of the effects of resource constraints. In some cases, uncertainty and decision variables are modeled explicitly as well. The main disadvantage of this approach is that the system and restoration process have to be simplified to be able to model the evolution of restoration with this approach. The system is simplified as a source node, demand nodes, and links in between. The process is simplified to only include the link repair phase, not for example, the initial inspection or damage assessment phases.

NEW SIMULATION-BASED RESTORATION MODELING APPROACH

In discrete event simulation (DES), the method used in this study, an artificial history of the system being modeled is generated and observations are collected to estimate system performance measures. The technique "bases simulations on the events that take place in the simulated system and then recognizes the effects that these events have on the state of the system" (Law [27]). DES is a dynamic simulation approach that can be either deterministic or stochastic In DES (as opposed to continuous time simulation), system state changes occur instantaneously at specific points in time.

The key elements in a discrete event simulation are entities, variables, and events. Objects of interest in the real system exist as *entities* in the simulation model (e.g., substations, pumping stations). *Resources* are a special type of entity that provide service to other objects of the system. *Variables* (e.g., damage state of a system component) define the system state. Variables can be of two kinds—*Global variables* apply to the whole system, and *attributes* are attached to specific entities. Simulations are based on keeping track of changes in certain variables as time proceeds (Ross [28]). Whenever an *event* (e.g., inspection or repair of a component) occurs, the values of variables are updated. The one-to-one mapping between objects in the complex system being modeled and their abstractions in the simulation model enables modeling the system under consideration quite accurately without the need to make significant simplifications. Simulation models are usually built by specifying the entities in a system and the processes they follow as they go through the system (Banks [29]). This implementation strategy is known as a process-interaction world view, and it enables including interactions between objects of the system into the model very easily.

The discrete event simulation approach for modeling post-earthquake restoration processes of lifelines builds on previous work but overcomes some past limitations. With this method, the restoration process depends not only on damage state, but also on available repair resources; hence, the effects of resource constraints can be considered. It allows spatial and temporal depiction of the restoration process so that one can end up with restoration curves for each region of the service area, rather than just one for the entire lifeline system. The method also enables explicit consideration of the effects of the utility company's decision variables, such as repair prioritization plans, mutual aid agreements, and number of repair materials to stockpile. Statistical variability and uncertainties associated with key parameters, such as, post-earthquake damage inspection durations, repair durations for each damaged component, time needed to replace components that can not be repaired, and amount of available resources are taken into account by defining these parameters as random variables with specified probability distributions. This enables quantification of uncertainty related with restoration time estimates, the importance of which Shinozuka [30] underlined. The interactions among lifelines has been observed to have considerable effect on post-earthquake restoration processes (Hada [31]) and the DES method is flexible enough that it could be extended into a multi-lifeline restoration model that can take into account interaction effects. The key disadvantages of this approach are that it may take a relatively long time to create a model for systems with a large number of entities and variables, and that, as with all models, the results are only as good as the data that goes into them. It may require more effort to obtain the necessary input data for a simulation model than a model that simplifies the system more.

ELECTRIC POWER RESTORATION MODEL

In this section, the discrete event simulation approach is applied to the LADWP electric power system. Efforts are underway to apply the same approach to the LADWP water supply system, and it could be applied to other lifelines as well. The details will differ in each application, but the model structure and types of elements will be the same. In the MCEER-LADWP electric power system damage model, only damage to high voltage substations is considered (Shinozuka [7]). It has been observed that these are the most vulnerable components of an electric power system, so this assumption should not cause considerable deviation from reality (Shinozuka [7]).

The electric power system restoration model was constructed using the simulation software Promodel [32]. It takes as input an initial damage state for a specified earthquake. Figure 2 shows a schematic of the anticipated output of this model—a dynamic map indicating how the level of functionality in each region of the service area changes over time during the restoration, and for each region, a restoration curve with uncertainty bounds for the system. Note that while the model is capable of creating this output, because certain required data are currently unavailable, at this time, the output includes the dynamic map and just one restoration curve with uncertainty bounds (like that in Figure 2b) for the whole service area. The model is currently being calibrated using Northridge earthquake data. After calibration, restoration time estimates and uncertainties associated with these estimates will be obtained for various initial damage and outage patterns that will be provided by other MCEER investigators.

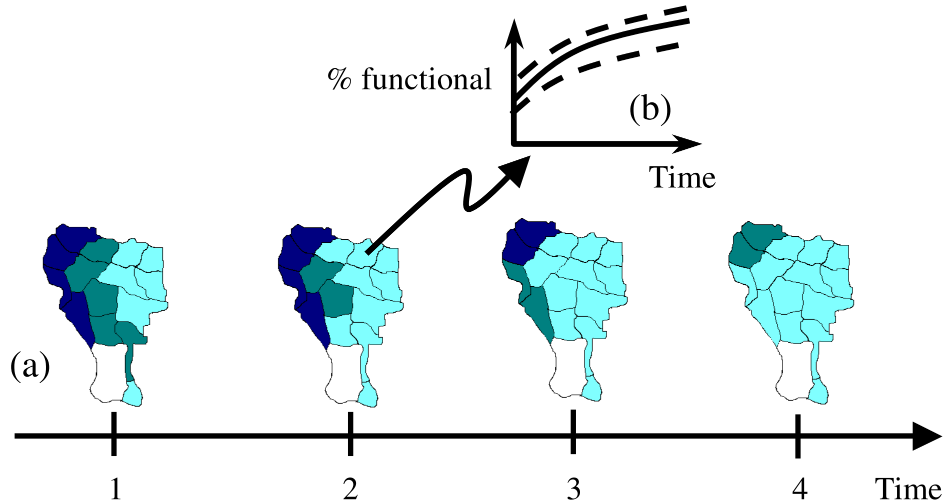

Figure 2. Expected Output of Restoration Model.
(Areas are shaded to indicate level of functionality; darker means less functional)

Before constructing the model, the authors collected a considerable amount of data about how LADWP responds after an earthquake to restore electric power. This information was gathered by studying the LADWP Electric Emergency Response Plan (LADWP [33]) and a report describing the company's experience in the Northridge earthquake (LADWP [34]), by visiting the company's facilities, and by interviewing the personnel in charge of post-disaster power restoration. Using this data, the details of electric power restoration model have been developed so that simulations imitate the restoration processes that take place in real world accurately.

Table 1 lists examples of the entities, attributes, resources, and events in the model. Each high voltage substation and generation station is an entity. The attributes of each generation station entity include, for example, type of generation station (e.g., steam, hydro), status before the earthquake (on or off), status after the earthquake, critical restart time limits, and distance from the epicenter of the earthquake. The attributes of substation entities include, for example, status right after the earthquake, distance from the epicenter, and number of circuit breakers, disconnect switches, and transformers in the substation that are damaged. These are the three substation components included in the damage model (Shinozuka [35]). On-duty substation operators, on-duty power generation operators, off-duty substation operators, damage assessment teams, repair teams, and different types of repair material are the resources in the model. The services they provide to the substations and generation stations include inspection, damage assessment, and repair.

The restoration of electric power systems can be divided into four main phases: (1) Initial inspection, (2) Damage assessment, (3) Repair, and (4) Reenergizing. These correspond to the events that take place in the simulation. First, on-duty operators inspect generation stations and substations. The duration of this service is defined as a random variable. At the end of this phase, the attribute indicating whether the entity is inspected or not is updated. Meanwhile, off-duty operators and damage assessment teams (DATs) become available at district yards and LADWP headquarters, respectively. District yards are service centers where repair materials are stored. These resources become available a specified time after the beginning of simulation because in previous earthquakes it has been observed that restoration personnel report back to work 0.5 to 1 hour after an earthquake. All off-duty resources can not be available immediately after the earthquake; rather their number increases as time goes on. This is taken into account by progressively increasing the number of available resources in the model. Off-duty operators are dispatched immediately to substations at which no on-duty operators are available. Priority is given to substations that are near the epicenter of the earthquake, and hence more likely to be damaged. Again at the end of inspection duration, which is defined as a random variable, the attribute indicating whether the entity has been inspected or not is updated.

Table 1. Examples of Electric Power System Model Components

Entities	Substations Power generation stations
Attributes of generation stations	Type of station Critical restart time limits Status after the earthquake Status before the earthquake Distance to earthquake epicenter
Attributes of substations	Damage level Status after the earthquake Status before the earthquake Distance to earthquake epicenter
Resources	On-duty substation operators On-duty generation station operators Off-duty substation operators Damage assessment teams (DATs) Repair teams Repair material
Events	Inspection Damage assessment Repair Reenergizing

In the second phase, DATs are dispatched to substations. Those inspected and reported to be damaged have priority, as do substations in the heavily shaken area. The duration of the damage assessment phase is defined as a random variable. At the end of this phase, the attribute indicating whether the entity has been inspected by the DATs or not is updated.

For the resources that are dispatched from district yards and LADWP headquarters, delays due to traveling are taken into account by defining them as movable resources in the model. These have the capability to travel along defined paths. Different travel speeds can be assigned to these resources along different portions of the travel path. This enables the inclusion of additional delays due to damage to roads and bridges.

Like off-duty substation operators, repair teams become available at district yards a specified time after the beginning of the simulation. In the third phase, the district yard closest to the heavily shaken area becomes the field command center. Repair material and repair personnel are moved from other district yards to the field command center once it is activated. Repair teams and repair material are dispatched from the field command center to the damaged substations that have been inspected by DATs. Priority is given to substations that are not heavily damaged. The duration of repair for each substation component included in the damage model is modeled as a random variable. The overall substation repair times are obtained by adding all the random component repair times after multiplying each by the corresponding number of damaged components. When repair is complete, the attribute indicating the damage level of the entity is updated.

The reenergizing phase starts once the initial inspection of generation stations is complete. On-duty operators at generation stations are in charge of reenergizing. Generators away from the epicenter of the earthquake are given priority, since it is likely that substations connected to these stations are not damaged. The load pick up durations for generation stations depend on the type of the station, status before the earthquake, and its black start capabilities. Black start capability describes how easily a generating unit can start up without any power supply from the power system. Once the station is ready to pick up load, the attribute indicating its status is updated, as are the status attributes of the undamaged substations that are connected to the reenergized station.

CONCLUSIONS AND POSSIBLE FUTURE EXTENSIONS

This paper describes a simulation-based model of the post-earthquake restoration process of the LADWP electric power system. The approach is generally applicable to modeling the post-disaster restoration process for other lifeline systems and hazards. Key advantages of this approach are its explicit representation of the company's decision variables, ability to produce spatially disaggregated restoration curves, representation of uncertainty in the restoration curves, explicit, relatively realistic modeling of the real-life restoration process, and flexibility to accommodate changes in the model.

The investigators are currently developing a similar post-earthquake restoration model for the LADWP water supply system. Future efforts might apply the approach to other lifelines and hazards. The simulation model may also be extended to develop a multi-lifeline restoration model that takes into account interaction effects, or integrated with an optimization model to provide guidance on the optimal way to conduct post-earthquake restoration of lifelines.

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