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Post-Earthquake Lifeline Service Restoration Modeling

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Summary

In this study, a simulation-based methodology is being developed to model post-earthquake restoration processes of lifelines as part of the MCEER research on Los Angeles Department of Water and Power's (LADWP's) electric and water supply systems. Post-earthquake restoration models play an important role in estimating the economic impact of earthquake damage to lifeline systems. This paper begins with a discussion of the available restoration modeling approaches, listing advantages and disadvantages of each. The new simulation-based methodology is described, and key innovations that distinguish it from previous approaches are explained. Finally, plans for possible future extensions are discussed.

Introduction

Following an earthquake, loss of infrastructure function can significantly disturb normal economic activity. The duration of functional loss is a critical determinant of the magnitude of economic disruption. Because of this, models of post-earthquake restoration processes are important in evaluating economic losses.

This study is part of the MCEER research that aims to develop and demonstrate an advanced, integrated earthquake loss estimation methodology for urban lifeline systems. The MCEER earthquake loss estimation methodology was first developed as part of the Memphis Light, Gas and Water Division (MLGW) demonstration project (Chang et al., 1996, 1999 and 2002). The current study is part of the LADWP demonstration project which is a continuation of MLGW project. The MCEER loss estimation methodology consists of three main models: (1) damage estimation model, (2) restoration model, and (3) direct-indirect economic loss estimation model. For each scenario earthquake, the loss estimation process from damage to direct economic loss is simulated multiple times within a Monte Carlo framework. Initial damage and outage patterns obtained using a Monte Carlo simulation approach (Shinozuka 1994) are the input to the restoration model. Updated damage patterns are the output of the restoration model. For updated damage patterns, flow and connectivity analyses are carried out to produce the corresponding updated outage patterns. These results are then input into the direct economic loss model of business interruption. Using average outage and direct economic loss data, indirect economic loss is evaluated. Finally, by combining these estimates with probabilistic hazard data, expected annual loss is obtained (Chang et. al., 1999).

The objective of this study is to develop improved models of the post-earthquake restoration processes of the electric and water supply systems. Each model uses estimates of physical damage to the system under consideration, and an understanding of the repair and recovery operations, to estimate expected restoration time, as well as the uncertainty surrounding this estimate. In these models, restoration processes are disaggregated both spatially and temporally, which enables incorporation of the temporal and spatial dimension of economic loss. Decision variables, such as repair prioritization plans and mutual aid agreements, are considered explicitly.

Successful completion of this study will help to improve the accuracy of estimates of economic loss due to earthquake damage, and will help guide improvement of the post-earthquake restoration processes for electric and water supply systems. Studying the effects of the decision variables on restoration time will help the LADWP to improve its post-earthquake restoration plans.

This study includes four main phases: (1) background research on available post-earthquake lifeline restoration modeling approaches and on other parts of the MCEER LADWP project with which this study directly interfaces, (2) information collection on how restoration takes place in reality, (3) development of restoration models, and (4) comparison of results with documented system performance in the 1994 Northridge and 1971 San Fernando earthquakes. Phases 1 and 2 of this study have been completed, and phase 3 is currently under development. The work that has been completed so far, and the future possible extensions of this study, are discussed in the following sections.

Previous Restoration Modeling Approaches

Four different approaches have been used previously in modeling post-earthquake lifeline restoration. The first method is based on statistical restoration curves. The other empirical approach is based on resource constraints. There also exist more theoretical approaches, such as, the Markov process approach and the network approach. The latter is mainly used for developing optimum restoration strategies. Each of these approaches is explained in more detail below.

In the statistical restoration curves approach, data obtained from previous earthquakes and/or from expert opinion are employed to fit restoration curves. This approach has been used in previous studies, such as, ATC-25-1 (1992), Chang et al. (1996) and Nojima et al. (2001). In ATC-25, restoration curves are constructed by using data sources excerpted from ATC-13 (1985) that are based on regression analysis of expert-opinion data obtained through an iterative questionnaire process. In Nojima et al. (2001), Gamma distributions are used as restoration curves, and parameters of the distributions are estimated as a function of damage level using data from previous earthquakes. Nojima et al. (2001) enables breaking down the single "system restoration curve" into many restoration curves depending on seismic intensity, and hence, spatially disaggregates the restoration process. In the statistical restoration curves approach, the primary determinant of system restoration time is ground shaking intensity. Issues such as personnel constraints and opportunities to reduce losses by speeding up or optimizing restoration are not considered (Chang et al., 1999).

In the deterministic resource constraint approach, the evolution of the restoration is modeled in a simplified way. The number of repairs that can be made in any time period is specified according to the number of repair personnel available. This approach allows depiction of restoration progress across both time and space, and enables exploring earthquake loss reduction in a variety of new directions, such as, speeding up total restoration times, prioritizing spatial sequencing of restoration, and developing mutual aid agreements (Chang et al., 1999). This approach has been employed in Isumi and Shibuya (1985), Ballantyne (1990), HAZUS – water distribution system section (NIBS 1997), and in Chang et al. (2002). In these studies, restoration processes are modeled deterministically, so the uncertainty associated with expected restoration time is not estimated. It has also been assumed that restoration processes involve only the repair phase. However, restoration processes are more complex than that in reality; they include phases such as damage assessment, and initial inspection as well.

Hoshiya (1981) and Isoyama et al. (1985) model an individual lifeline's functional performance in the post-earthquake period using discrete-state, discrete-transition Markov processes. In later studies, such as Kozin and Zhou (1990) and Zhang (1992), a discrete-state, discrete-transition Markov process is employed to model evolutionary restoration process of various lifelines together as a system. Zhang (1992) takes into account the effects of interactions between various lifelines as well, by considering the transition probability of each subsystem not only as function of allocated resource but also as a function of the states of other subsystems. The Markov processes approach requires that the model parameters and probability values are estimated accurately. Even if adequate databases are established for this purpose, converting available data into the model parameters and probability values can be a real challenge.

In the network approach, a system consists of a supply node and a number of demand nodes. These are connected to each other via links that can be damaged or fully functional. In Nojima and Kameda (1992), graph theory (Minimum Spanning Tree and Shortest Path Tree) and optimization theory (Horn's Algorithm (Horn 1972)) are combined to develop an optimal restoration plan. In Okumura (1994), the proposed optimal repair sequencing method is based on the connectivity of a tree-shaped network and involves simplified flow analysis of the network as an approximate global optimization strategy. The network approach enables both spatial and temporal disaggregation of restoration processes and consideration of the effects of resource constraints. The main disadvantage is that the system (as source node, demand nodes, and links in between) and restoration process (only link repairs considered, other phases ignored) have to be simplified to be able to model the evolution of restoration with this approach.

Proposed Restoration Modeling Methodology

In this study, the post-earthquake restoration processes are modeled for electric and water supply systems by discrete event simulation (DES). DES is a dynamic simulation approach which can be either deterministic or stochastic. This simulation 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 and Kelton, 1991). In DES, system state changes occur instantaneously at specific points in time. The proposed methodological approach for modeling post-earthquake restoration processes of lifelines includes a number of improvements and expansions to the previously developed approaches.

In the proposed modeling approach, the restoration process does not only depend on the damage state but also on the available repair resources. Hence, the effects of resource constraints are considered. It allows spatial and time wise depiction of the restoration process, as well as explicit consideration of the effects of decision variables, such as repair prioritization plans and mutual aid agreements.

The proposed methodology is not deterministic. Statistical variability and uncertainties associated with key parameters, such as, post-earthquake damage inspection durations, start and finish time for repair of each damaged component, time needed for replacement of components that cannot be repaired, and resource allocations are taken into account by defining these parameters as probability distributions. This enables quantification of uncertainty in the final restoration time estimates.

The key elements in a discrete event simulation are *variables* and *events*. Variables (e.g., damage state of various system components) define the system state and simulations are based on keeping track of changes in certain variables as time proceeds. Whenever an event (e.g., repair of a component) occurs, the values of variables are changed or updated. Objects of interest in the real system exist as *entities* in the simulation model (e.g., substations, pumping stations). *Resources* (e.g., repair teams) are a special type of entity: they provide service (e.g., damage assessment) to other objects of the system. Variables can be of two kinds, global variables that apply to the whole system, and attributes that are variables attached to entities. The one-to-one mapping between objects in the complex system being modeled and their abstractions in the simulation enables modeling the system under consideration quite accurately without the need to make considerable simplifications.

Table 1 lists the main restoration model components for electric power and water supply systems. Each entity obtains resources based on its priority level, which is a function of its attributes. Once an entity gets a resource, the resource becomes unavailable to other entities for the duration of the restoration phase it is in charge of. These durations are defined as random variables in the simulation, as mentioned above. When the resource completes its duty, the attributes related to the corresponding restoration phase are updated, and the resource moves to the next entity. Each simulation continues until the restoration process is complete. For each initial damage pattern, the restoration simulation is repeated many times; hence, uncertainty associated with restoration time estimates is quantified.

Table 1. List of electric and water supply system model components

	Electric Power System	**Water Supply System**
Entity	Substations Power Generation Stations	Pipes Pumping Stations Tanks Reservoirs Regulator Stations
Attributes	Damage Level Status (on/off) after the Earthquake Status (on/off) before the Earthquake Distance to Earthquake Epicenter	Damage Level Distance to Earthquake Epicenter Distance to Source Status after the Earthquake
Resource	On-duty Substation Operators On-duty Generation Station Operators Off-duty Substation Operators Damage Assessment Teams Repair Teams Repair Material	On-duty Personnel at Reservoirs Reservoir Inspection Teams Damage Assessment Teams Transmission Operators Repair Teams Repair Material
Event	Inspection Damage Assessment Repair Re-energizing	Inspection Valve Shut Down Damage Assessment Repair

The model development phase of this study is still in progress, so no simulation outputs are presented here. The expected output of each simulation is a time history of the restoration process. This includes information about both the system components and the repair crews, for example at which instant of the repair process, repair of each system component is completed, what is the utility level of each repair crew, etc. Using this information, spatially disaggregated restoration curves will be developed, from which estimates of overall system restoration time and uncertainty associated with these estimates will be obtained.

Two possible directions in which the current study can be expanded in the future are: (1) by extending the proposed methodology to develop a multi-lifeline restoration model that takes into account interactions between lifeline systems, and (2) by developing and implementing optimization methods to examine both optimal post-earthquake restoration of lifelines systems and optimal pre-earthquake policies. Simulation models are usually built by specifying the entities in a system and the processes they follow as they go through the system. This implementation strategy is known as a process-interaction world view, and it will enable development of a multi-lifeline restoration model that very easily takes into account interaction effects. The second possible future expansion involves the development of an enhanced approach for discrete, simulation-based optimization. Application of this methodology would be beneficial to LADWP by enabling them to improve their post-earthquake restoration capabilities. It would also improve the earthquake resiliency of the community, by reducing the economic losses associated with earthquakes.

Concluding Remarks

A simulation-based methodology being developed for modeling post-earthquake restoration processes of electric power and water supply systems is described. Key innovations that distinguish this methodology from previously developed methodologies are: (1) temporal and spatial disaggregation of the restoration process, which enables incorporation of the temporal and spatial dimension of loss, (2) explicit consideration of the decision variables, which enables exploration of how post-event mitigation strategies, such as, mutual aid agreements and spatially prioritized restoration can reduce total economic loss, and (3) incorporation of statistical variations and uncertainties associated with key factors, which enables quantification of uncertainty associated with restoration time estimates.

Acknowledgements

This research was carried out under the supervision of Prof. Rachel Davidson of Cornell University, and 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.

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