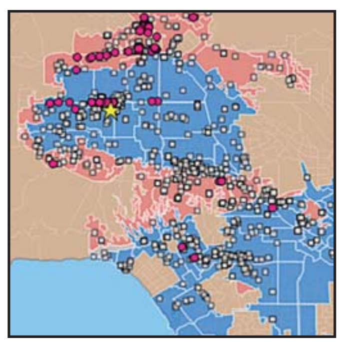
MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

ISSN 1520-295X

Post-Earthquake Restoration of the Los Angeles Water Supply System

by
Taronne H.P. Tabucchi and Rachel A. Davidson



Technical Report MCEER-08-0008
March 7, 2008

This research was conducted at Cornell University and was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation under award number EEC 9701471.

MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS

Post-Earthquake Restoration of the Los Angeles Water Supply System

by

Taronne H.P. Tabucchi[1] and Rachel A. Davidson[2]

Publication Date: March 7, 2008
Submittal Date: January 22, 2008

Technical Report MCEER-08-0008

Task Number 10.3.2

NSF Master Contract Number EEC 9701471

1 Graduate Student, School of Civil and Environmental Engineering, Cornell University
2 Associate Professor, Department of Civil and Environmental Engineering, University of Delaware; Former Assistant Professor, School of Civil and Environmental Engineering, Cornell University

MCEER
University at Buffalo, The State University of New York
Red Jacket Quadrangle, Buffalo, NY 14261
Phone: (716) 645-3391; Fax (716) 645-3399
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

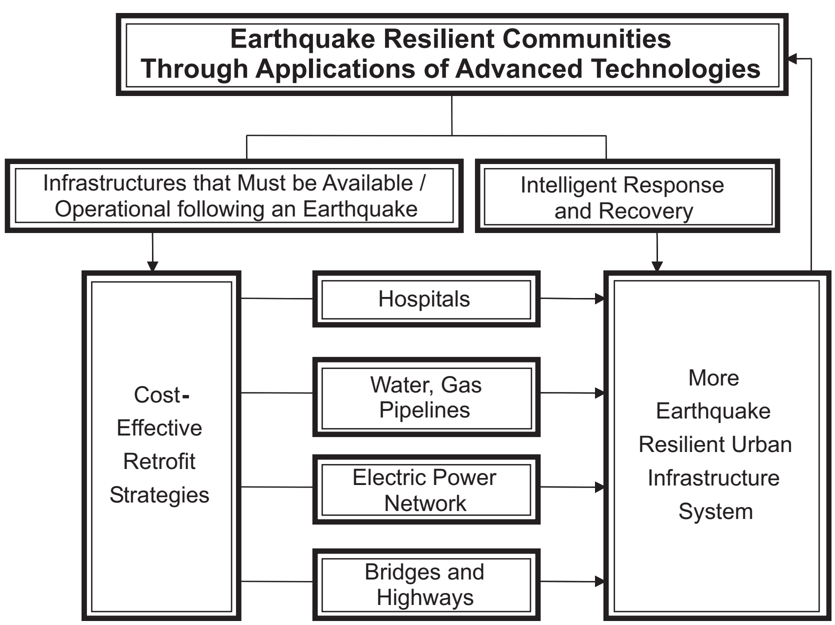
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report describes a discrete event simulation model of post-earthquake restoration developed for the Los Angeles Department of Water and Power (LADWP) water supply system. The LADWP water organization, water supply system, and post-earthquake restoration process were examined in detail to provide the basis for the restoration model. For a particular earthquake, the model uses information about damage to the system and the resulting hydraulic flow obtained from the Graphical Iterative Response Analysis for Flow Following Earthquakes (GIRAFFE) model that was also developed for the LADWP system. Throughout the simulation, the model interacts with GIRAFFE to receive updates of the system functionality at specific times as the restoration process proceeds and damage is repaired. Several different types of output are provided, including system and subregion restoration curves; spatial distribution of restoration; material usage; crew usage; average time each customer is without water; and time to restore the system and subregions to 90%, 98%, and 100%. It can also include damage uncertainty by combining the output from runs for multiple realizations of damage associated with a single earthquake. The model can be used to help estimate economic and societal losses due to water supply system outages, and to evaluate the effectiveness of possible restoration improvement strategies. Ten simulations of the restoration model were run using real damage data from the 1994 Northridge earthquake as input, and the results were compared to the actual restoration that took place following Northridge. The average spatial distribution of restoration roughly matches what occurred in 1994.

ABSTRACT

The purpose of this report is to develop a discrete event simulation model of post-earthquake restoration for the Los Angeles Department of Water and Power (LADWP) water supply system. Discrete event simulation, a new approach to modeling post-disaster lifeline restoration, offers many benefits for restoration modeling compared to alternative methods. The water supply system and restoration process are represented in great detail with few simplifications. The utility company's decision variables (e.g., number of repair crews, repair prioritization rules) are included explicitly, allowing exploration of their effects on the speed of the restoration. Restoration times are estimated separately for each region within the service area, and uncertainty in the process is modeled explicitly.

With a service area of more than 1,200 km^2 and 12,000 km of pipelines, the LADWP water supply system is the largest municipal system in the United States. Extensive review of the LADWP water organization, water supply system, and post-earthquake restoration process was conducted. This review provided the basis for the restoration model. Crews, tasks, and the different phases in the restoration process came directly from discussions with LADWP personnel and the water organization's emergency response plans.

For a particular earthquake, the restoration model takes as input information about damage to the system and the resulting hydraulic flow, both of which are provided by the *Graphical Iterative Response Analysis for Flow Following Earthquakes* (GIRAFFE) model that was developed for the LADWP system (Shi 2006, Wang 2006). Throughout the restoration simulation, the model interacts with GIRAFFE periodically in order to receive updates of the system functionality at specific times as the restoration process proceeds and damage is repaired.

The restoration model provides several different types of output including system and subregion restoration curves; spatial distribution of restoration; material usage; crew usage; average time each customer is without water; and time to restore the system and subregions to

90%, 98%, and 100%. It can also include damage uncertainty by combining the output from runs for multiple realizations of damage associated with a single earthquake. The model can be used to help estimate economic and societal losses due to water supply system outages, and to evaluate the effectiveness of possible restoration improvement strategies.

Ten simulations of the restoration model were run using real damage data from the 1994 Northridge earthquake as input, and the results were compared to the actual restoration that took place following Northridge. The average spatial distribution of restoration roughly matches what occurred in 1994. As in real life, the areas experiencing longer outages in the model are mainly in the north of the system service area or around the San Fernando Valley. The system restoration curves did not match exactly, as the range of outputs from all 10 runs of the restoration model shows that the restoration occurs too quickly, especially during the first day after the earthquake. Possible future model modifications that may improve the calibration are discussed.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

Figure **Title** **Page**

LIST OF FIGURES (CONT'D)

Figure **Title** **Page**

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Introduction

Earthquakes can cause widespread damage to water supply systems resulting in extensive service interruptions that can last for days. In the 1994 Northridge earthquake, the Los Angeles Department of Water and Power (LADWP) sustained more than 70 incidents of damage to trunk lines, 1,013 incidents of damage to distribution lines, and damage to 5 water tanks (Shi 2006). Approximately 500,000 people (14% of those served by LADWP) lost water service (McReynolds and Simmons 1995). It took five days to restore water to 99% of customers and repairs continued for months, costing about $41 million (McReynolds and Simmons 1995, Lund et al. 2005). About 18% of surveyed businesses that closed indicated that loss of water was one reason they closed (Tierney 1997), suggesting that indirect losses associated with water supply damage were substantial as well. The first citywide water purification notice was issued in Los Angeles within three hours of the earthquake and it lasted for up to 12 days in some areas (McReynolds and Simmons 1995).

Loss of water service and water purification notices in events like the Northridge earthquake can significantly disrupt drinking supply, sanitation, hospital functioning, industrial processes, and many other aspects of daily life. In fact, surveys suggest that water supply is one of the elements of the built environment that residents and business owners consider to be most important to remain functional after an earthquake (Tierney 2000, Argothy 2003, Tierney and Dahlhamer 1998). Both the number of post-earthquake water outages and their durations are important in determining the final impact of an event.

This report describes a new discrete event simulation model of post-earthquake restoration for the LADWP water supply system. Discrete event simulation offers many benefits for restoration modeling compared to alternative methods. The water supply system and restoration process are represented in great detail with few simplifications. The utility company's decision variables (e.g., number of repair crews, repair prioritization rules) are included explicitly, allowing exploration of their effects on the speed of the restoration. Restoration times are estimated separately for each region within the service area, and uncertainty in the process is modeled explicitly. This approach to modeling post-disaster lifeline restoration is new. There are just two applications in the literature, both to electric power systems (Newsom 1977, Çağnan and Davidson, 2007, Çağnan et al. 2006). Water supply systems, however, introduce additional challenges when developing a discrete event simulation model of the restoration process. Among the most important differences when addressing water supply instead of electric power, are: (1) many more components of the system are damaged, (2) the ability to reroute around and isolate damage is important and more difficult to capture, (3) restoration decisions depend on serviceability, so damage and restoration models must be coupled, and (4) the restoration process lasts longer and thus, modifications to the plan are made repeatedly.

1.2. Objectives

The specific objectives of this study are to:

1. Understand and document the real-life post-earthquake water supply restoration process used by the Los Angeles Department of Water and Power (LADWP).
2. Develop a discrete event simulation model of the LADWP post-earthquake water supply restoration process. For a given earthquake, output of the model should include: (a) restoration curves (percentage of demand met vs. time) with estimates of uncertainty, (b) the spatial pattern of restoration, and (c) a summary of crews and repair materials required. It should be possible to use the model to evaluate the effectiveness of restoration improvement activities in future earthquakes.
3. Calibrate the restoration model using observations from the 1994 Northridge earthquake.

1.3. Expected Significance

The research presented in this report offers four primary contributions: (1) advancing the state-of-the-art in post-disaster lifeline restoration modeling, (2) improving post-earthquake loss estimation and resilience assessment, (3) helping utilities identify ways to improve post-earthquake restoration, and (4) supporting post-earthquake fire modeling.

First, as one of the only applications of discrete event simulation to post-disaster lifeline restoration modeling, and the first for water supply in particular, this research helps establish this relatively new, valuable method for addressing lifeline restoration. It extends the previous work on post-earthquake electric power restoration modeling by addressing many new challenges associated with water supply specifically, thus advancing the state-of-the-art in lifeline engineering. Among those challenges are accommodating thousands of entities (compared to tens in electric power) and a corresponding increase in complexity of the system and the restoration process; coupling the restoration model with a damage and functionality estimation model; and incorporating rerouting and damage isolation explicitly.

Second, the restoration model developed in this study can be used to improve the quantitative estimates of restoration times that are required to estimate economic and societal losses due to water supply system outages. This study is part of a Multidisciplinary Center for Earthquake Engineering Research (MCEER) effort to assess community earthquake resilience (Bruneau et al. 2003). A key dimension of reslience is rapidity, the speed with which response and recovery occur. The restoration model developed in this report will improve the assessment of rapidity for the water supply system in particular and lifelines in general.

Third, by explicitly representing the actual process that the utility company goes through to restore water service, the model can help identify ways to improve the restoration process in future earthquakes and evaluate the relative effectiveness of those strategies. The restoration process is complicated by the many decisions that must be made simultaneously, in a short time frame, with limited information, and under adverse conditions (in the aftermath of a major earthquake). Each utility company has relatively infrequent experiences with major earthquakes and each event is different. Thus, it will be valuable to be able to experiment with different strategies in a risk-free, virtual environment, and to examine the effects of different decisions on the restoration process.

Finally, the availability of water supply is a key input to any post-earthquake fire model. Since the water supply restoration model developed in this report provides spatially disaggregated estimates of water service at each time step in the post-earthquake period, it can be useful in supporting post-earthquake fire models.

1.4. Post-disaster Lifeline Restoration Modeling Methods

Available post-disaster restoration lifeline models can be grouped into six main approaches: (1) empirical curve fitting, (2) deterministic resource constraint, (3) Markov, (4) statistical regression, (5) optimization, and (6) simulation. Each of these approaches is described briefly in this section. More thorough reviews are available in Çağnan (2005), Liu (2006), and Xu et al. (2007). Liu (2006) updates the earlier review by Çağnan (2005), including the addition of the statistical regression approach. Xu et al. (2007) provides an in-depth review of the optimization approach.

In the empirical curve fitting approach, data obtained from previous events and/or expert opinion are employed to fit restoration curves, and it is assumed that those curves represent future restorations. 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. Some studies have modeled the restoration process of individual or groups of lifelines by assuming they follow a discrete-state, discrete-transition Markov process. Liu et al. (2007) offer the only example of a statistical approach to restoration modeling, applying it to electric power systems in hurricanes and ice storms. They fitted accelerated failure time (AFT) models using power company data from past storms. The models can be used to predict the duration of each probable outage in a storm, and by aggregating those estimated outage durations and accounting for variable outage start times, restoration times can be estimated for each county or other subregion of the service areas. While all the other approaches focus on descriptively modeling the current restoration process, optimization aims to determine the "best" way to conduct a restoration process in terms of, for example, how to prioritize repairs and how many of each type of restoration crew to have.

Monte Carlo simulation has been used in a simplified way to estimate post-storm electric power restoration. A simplified version of the storm restoration process is simulated using estimated failure rates and mean times to repair and switch. Newsom (1977) presents early work on post-earthquake electric power restoration using discrete event simulation, but interestingly, no other studies could be found that use or even mention that approach until almost 30 years later. As mentioned earlier, Çağnan and Davidson (2007) and Çağnan et al. (2006) present a discrete event simulation model of the post-earthquake restoration process for the Los Angeles Department of Water and Power electric power system.

Based on potential uses of a restoration model, a detailed study of real-life restoration processes, and a comparison of available methods, Çağnan (2005) defined a list of desirable features for a post-disaster restoration model. These attributes can be useful for comparing and evaluating different restoration modeling methods. It is desirable for a restoration model to (based on Çağnan 2005):

- Be usable in a predictive mode, before an in-field damage assessment is complete.
- 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 crews of different types, amount of repair materials of different types, and repair prioritization rules.
- Produce different restoration curves for each subregion within the service area rather than just one curve for the whole system. This allows more precise modeling of the economic and social impact resulting from service interruptions.
- Represent the uncertainty in the restoration time estimates.

- Be based on and validated with real experiences and/or data.
- Limit the extent to which simplifying assumptions about the infrastructure system and restoration process are required and 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 it can easily accommodate multi-lifeline interactions, changes in the restoration process, or changes in the data.

One of the key advantages of the discrete event simulation approach is that it does not requiring simplifying representation of the infrastructure system or the restoration process the way the other methods do. Some of the simplifications adopted in other methods may lead to large errors. For example, in most applications using the other methods, rerouting around and isolating damage, two parts of the process that can significantly affect restoration times, are neglected. While the statistical regression approach implicitly accounts for all the subtleties of the process, it cannot be applied for earthquakes unless a great deal more data becomes available, and it does not allow one to examine the effect of the utility's decision variables on the restoration.

It can be quite time-consuming to develop a discrete event simulation model and the model itself is system-specific. However, through sensitivity analysis one can use a discrete event simulation model to identify the most influential features of the restoration process and draw more general conclusions. One could also potentially use a discrete event simulation model to calibrate other simpler models.

1.5. Organization of the Report

Chapter 2 presents relevant background about the Los Angeles Department of Water and Power (LADWP). It includes descriptions of the physical system, the organization, and the post-earthquake restoration process. The discrete event simulation model and efforts to calibrate it using data from the 1994 Northridge earthquake are described in Chapter 3 and 4, respectively. The key contributions and avenues for future work are summarized in Chapter 5.

CHAPTER 2

LOS ANGELES DEPARTMENT OF WATER AND POWER

2.1. Introduction

This chapter presents relevant background about the Los Angeles Department of Water and Power (LADWP) water supply system. After a brief description of the physical system, two models important for understanding the restoration model are described. H2ONET is a hydraulic network model used within LADWP and GIRAFFE is an earthquake damage and functionality estimation model developed for the LADWP system. The LADWP organization is then described briefly, emphasizing aspects relevant for post-earthquake restoration. A detailed discussion of the post-earthquake restoration process follows, including the different types of crews involved in it and the process they follow. This understanding of the LADWP system, organization, and its post-earthquake restoration process are the basis for the restoration simulation model described in Chapter 3.

2.2. LADWP Water System

Established in 1902, the Los Angeles Department of Water and Power is the country's largest municipal utility. During the 2005-2006 fiscal year, the LADWP water supply system provided water to about 680,000 customers, representing 3.9 million people in a service area of approximately 1,200 km^2 (Figure 2.1) (LADWP 2007). In a typical summer or winter day, it supplies about $2.5(10^6)$ m^3 or $1.2(10^6)$ m^3 of water, respectively (Wang 2006). In 2004-2005, residential, commercial/governmental, and industrial uses accounted for 72%, 25%, and 3% of the water consumption, respectively (LADWP 2007). The key features of the LADWP water system necessary for understanding the restoration model are summarized in this section. Wang (2006) provides a more detailed description.

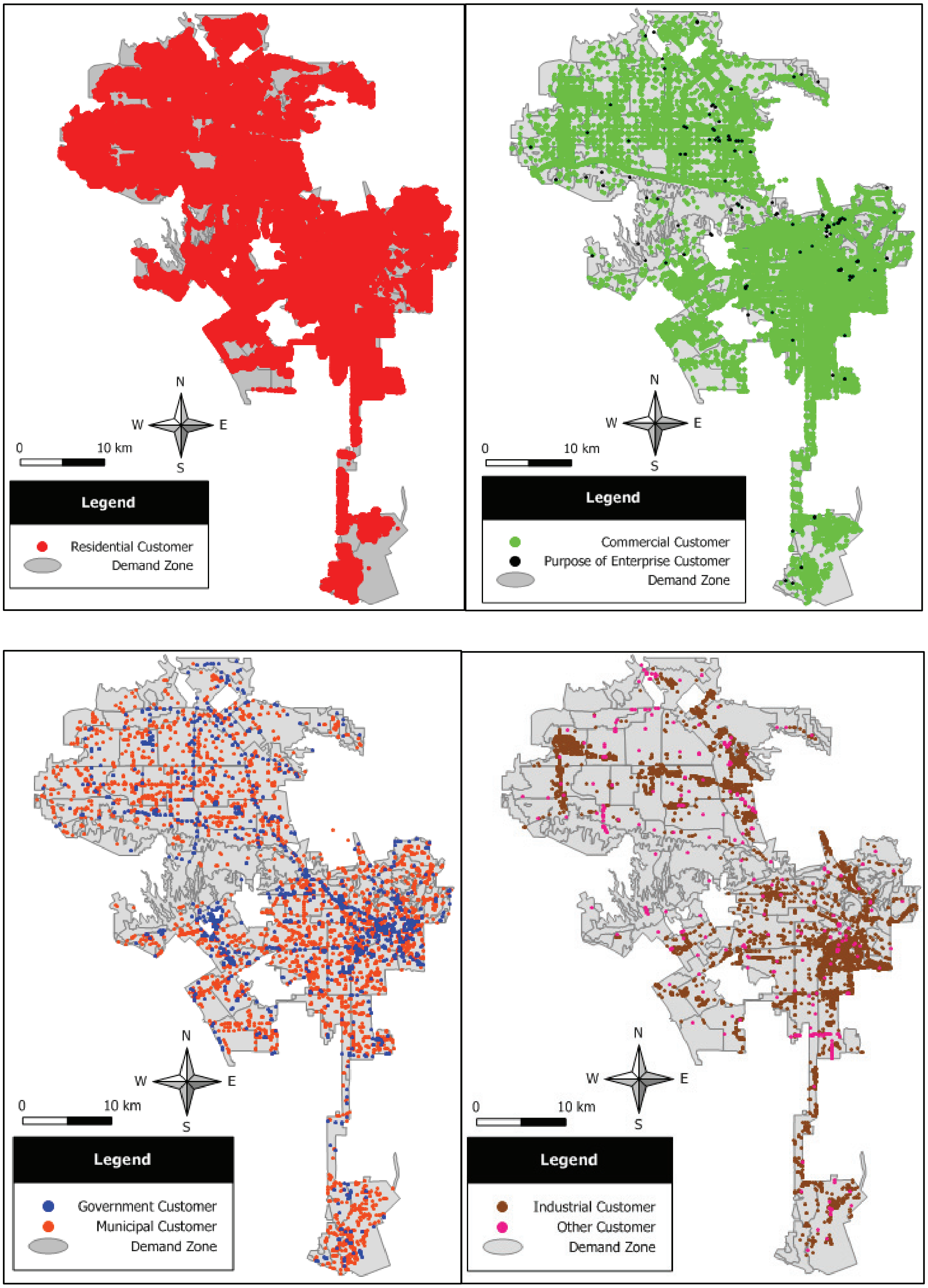


Figure 2.1. LADWP Customers Mapped by Type: Residential, Commercial, Purpose of Enterprise, Government, Municipal, Industrial and Other

The three main water sources for the system are the Los Angeles Aqueducts, the Metropolitan Water District (MWD), and local groundwater wells, providing about 48%, 41%, and 11% of the total water supply, respectively, in 2004-2005 (LADWP 2007). Water from the First and Second Los Angeles aqueducts and the California aqueduct enters the LADWP system at the Van Norman Complex (Figures 2.2 and 2.3), north of the San Fernando Valley, where it is treated by the LADWP Los Angeles Aqueduct Filtration Plant (LAAFP) and then distributed to the rest of the system. Water purchased from the MWD comes from the Colorado and California aqueducts. Figures 2.3 and 2.4, respectively, show the locations of the LADWP/MWD connections and the local groundwater wells.

LADWP divides its service area into 5 major water districts: West Valley, East Valley, Western, Central, and Harbor (Figure 2.5). The water system is also divided into 13 subsystems (Figure 2.6), which to meet the pressure requirements of a large service area with elevations that range from 0 to 735 m (1 to 2,411 ft), are further divided into 106 pressure zones (Figure 2.7). Each pressure zone is numbered after the highest hydraulic grade (sum of pressure and elevation heads) in it, in units of feet. In general, the hydraulic grades decrease from the north to the south, with the exception of the Santa Monica Mountains area. While 75% to 77% of pressure zones (based on water consumption), are gravity-fed, those located in the mountainous areas, where the elevations are high and vary greatly, are dominated by pressure zones fed by pump stations (Wang 2006) (Figure 3.3).

To distribute water throughout its service area, the LADWP water supply system includes approximately 300 regulator stations, 73 pump stations, 110 tanks and small reservoirs (Figure 2.4). It includes approximately 7,142 mi. (11,494 km) of pipe line—5,635 mi. (9,069 km) up to 12 in. (305 mm) in diameter, 972 mi. (1,564 km) 12 to 16 in. (406 mm) in diameter, and 535 mi. (861 km) larger than 16 in. in diameter. The four most common pipe diameters are 6 in. (152 mm) (3,109 mi. (5,003 km)), 8 in. (203 mm) (1,827 mi. (2,940 km)), 12 in. (791 mi. (1,273 km)),

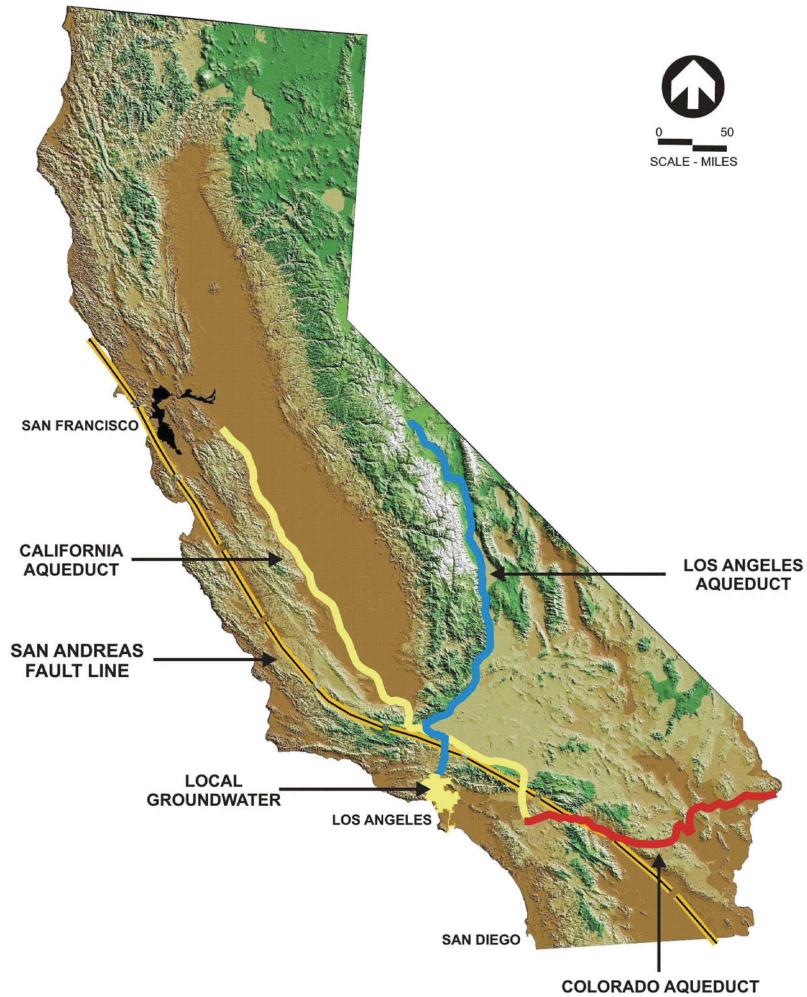


Figure 2.2. Water Sources for LADWP Water System (Source: Wang 2006)

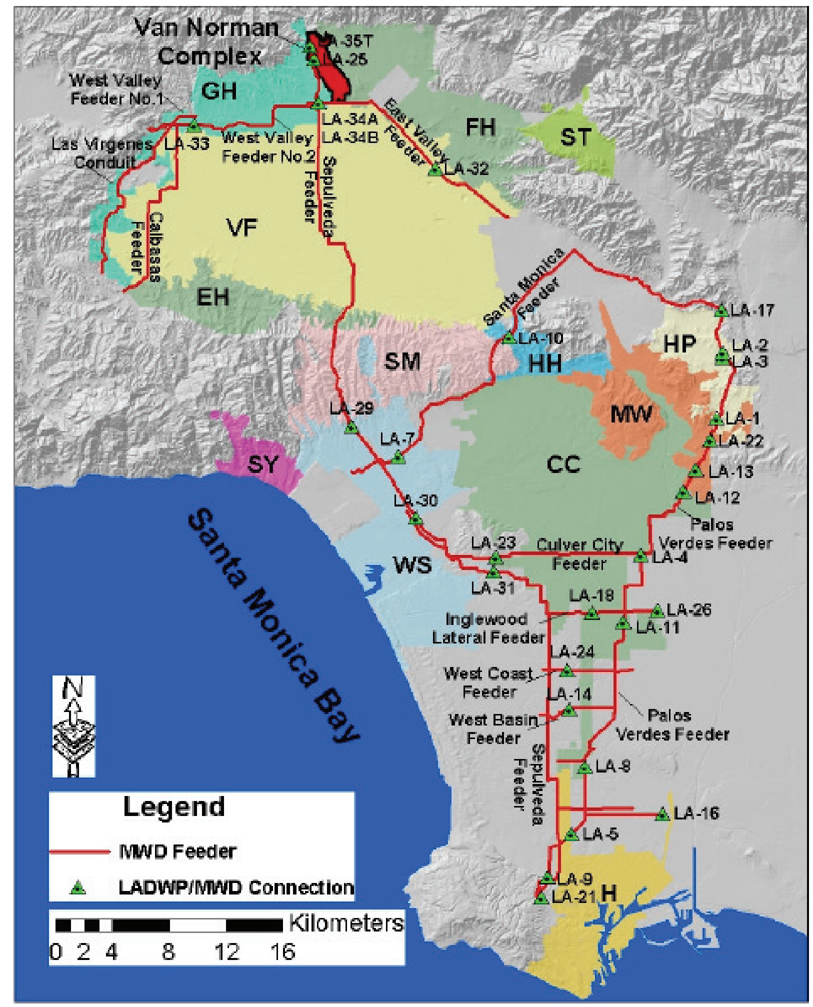


Figure 2.3. LADWP Service Area with MWD Connections (Source: Wang 2006)

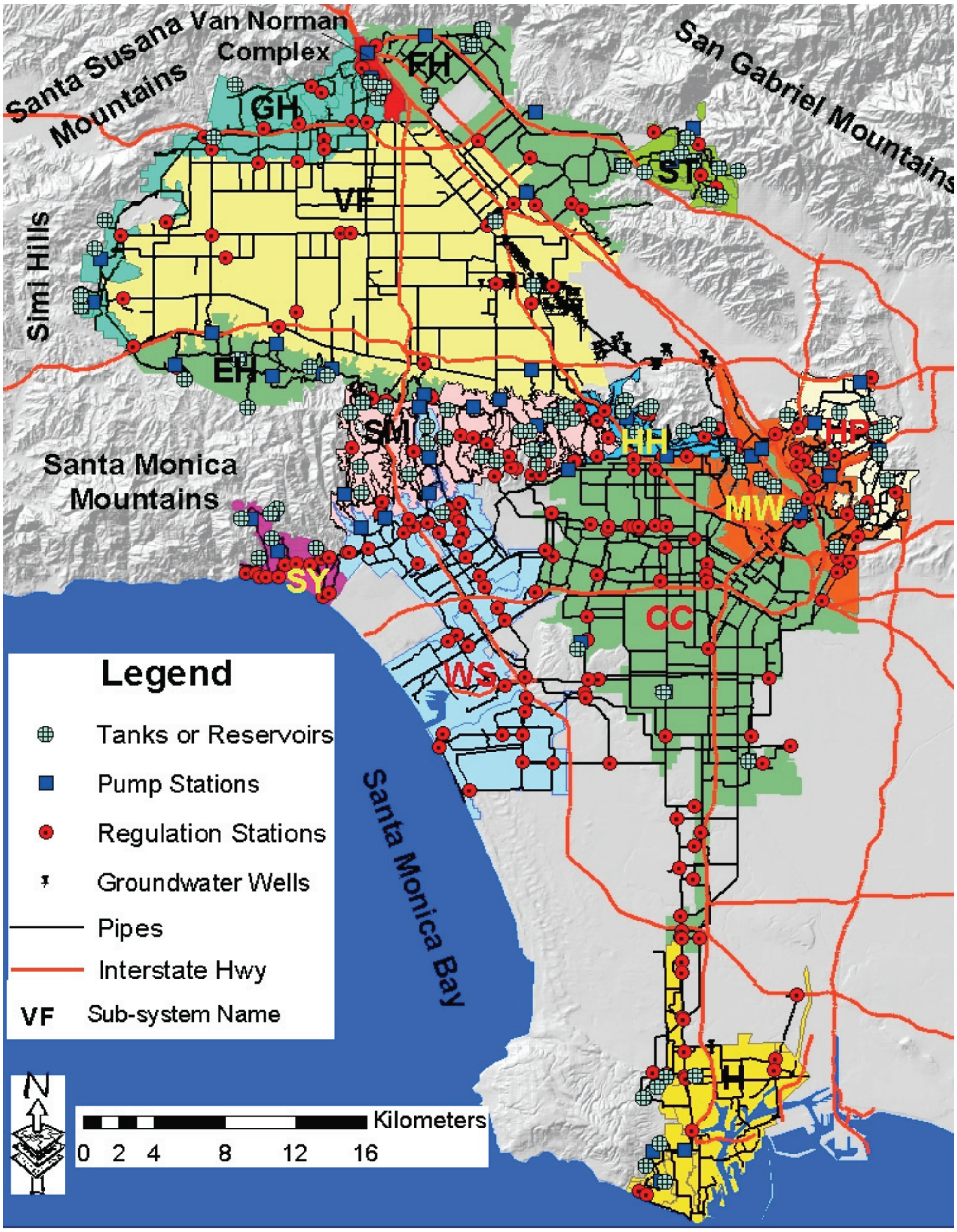


Figure 2.4. Major LADWP Water Supply System Facilities (Source: Wang 2006)

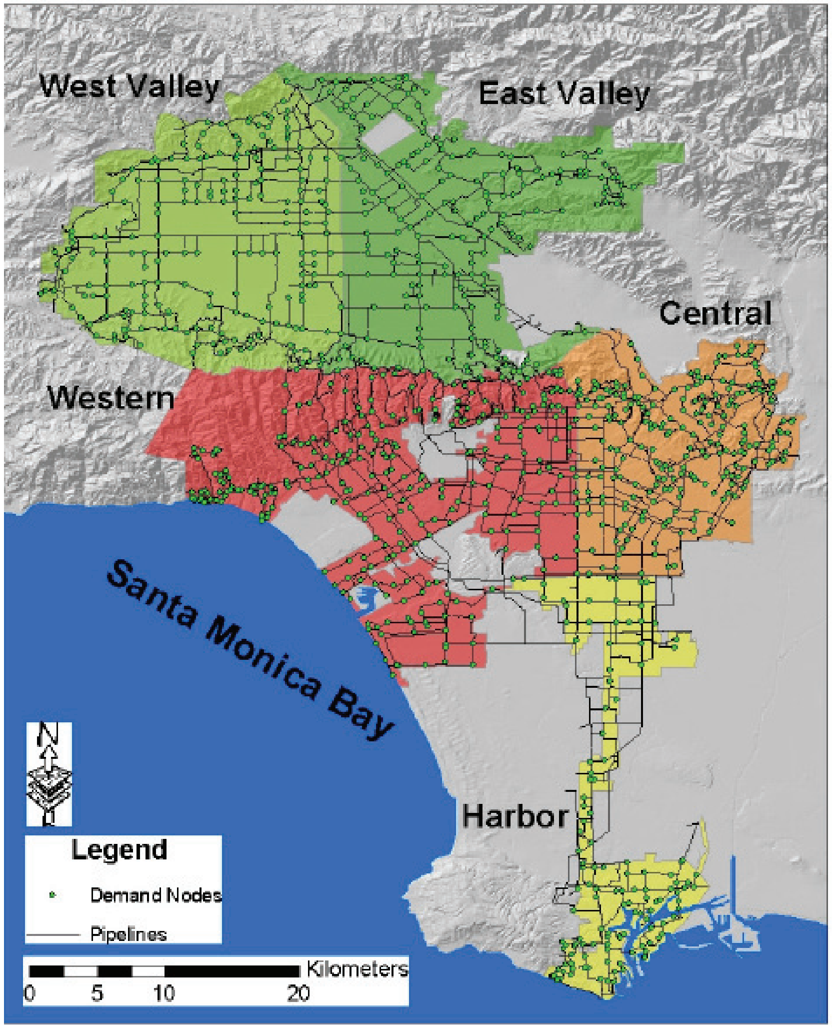


Figure 2.5. LADWP Service Area Divided into 5 Water Districts (Source: Wang 2006)

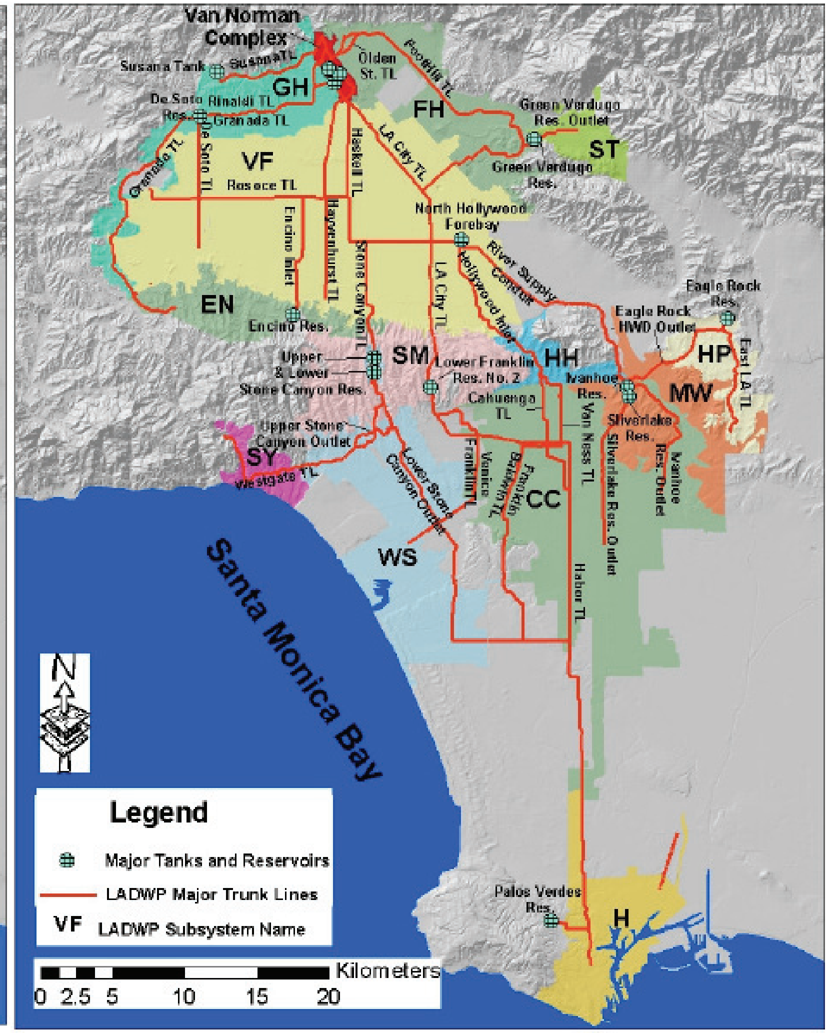


Figure 2.6. 13 Subsystems and Major Trunk Lines (Source: Wang 2006)

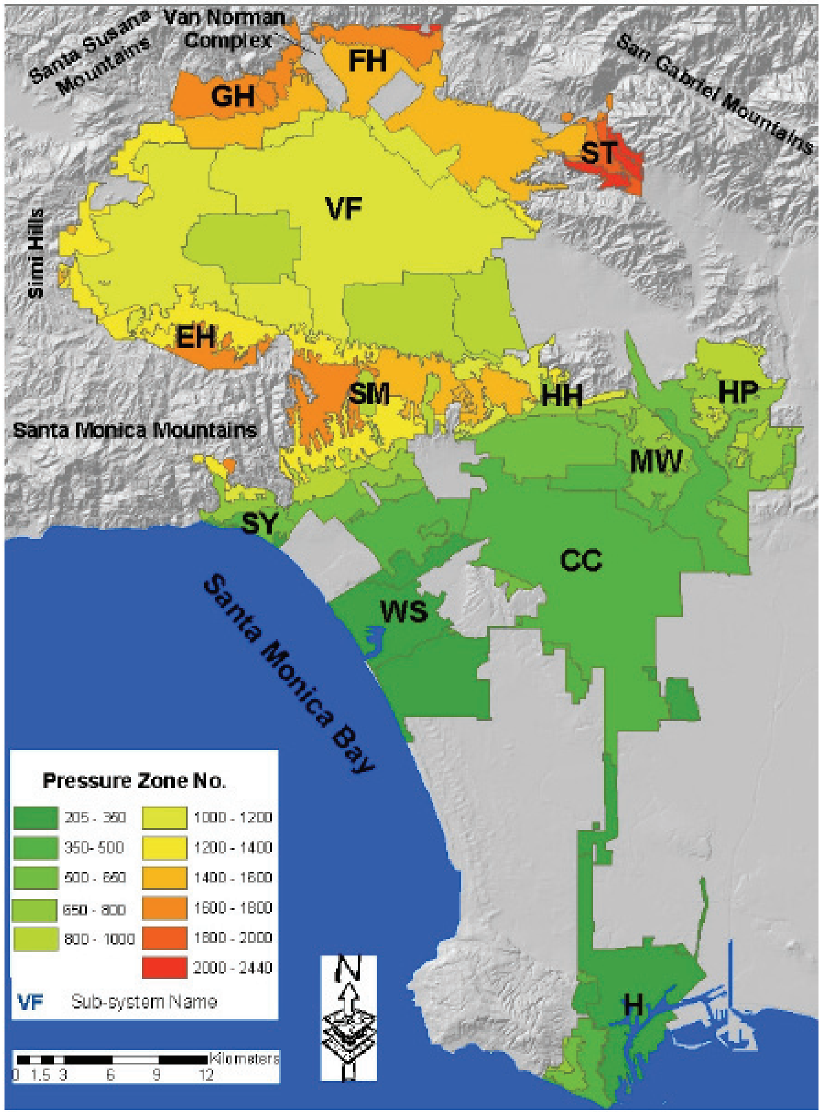


Figure 2.7. LADWP Pressure Zones (Source: Wang 2006)

and 4 in. (102 mm) (628 mi. (1,011 km)). Major trunk lines are the pipelines that are the sources for each of the 13 subsystems (Figure 2.6), minor trunk lines are the remaining pipelines with diameters of at least 24 in. (610 mm) (sometimes less in the Santa Monica Mountains region), and the distribution pipelines have diameters of less than 24 in. (610 mm) (Jeon and O'Rourke 2005).

2.3. LADWP Water System Models

The restoration model makes use of two computer models that have been developed for the LADWP water system: the hydraulic network model, H2ONET, and the earthquake performance simulation model, GIRAFFE. They are described briefly in this section.

2.3.1. H2ONET Hydraulic Network Model

A hydraulic network model called H2ONET was developed for the LADWP water supply system and is used by LADWP engineers for planning and analysis. In the 2002 version used in this work, H2ONET explicitly models 2,186 km (1,358 mi.) of pipeline, 230 regulator stations, 110 tanks and reservoirs, 151 local groundwater wells, and 73 pump stations (Figure 2.4) (Wang 2006). The size of the LADWP water supply system does not allow for the explicit modeling of all pipelines within H2ONET. As a result, more than 10,000 km (6,214 mi.) of the smaller diameter pipeline are represented by 1,052 demand nodes within the model. Each demand node is considered to represent an area of distribution pipelines (Figure 2.8). Figure 2.9 shows a portion of the real LADWP system with distribution lines and demand nodes. The demand nodes represent from about 1 to a couple hundred kilometers of distribution pipeline, with an average of about 35 km (22 mi.) per node. H2ONET contains more than 10,000 links and approximately 9,300 nodes. Figure 2.4 shows all of the facilities and pipeline modeled in H2ONET, and Figure 2.5 shows the demand nodes.

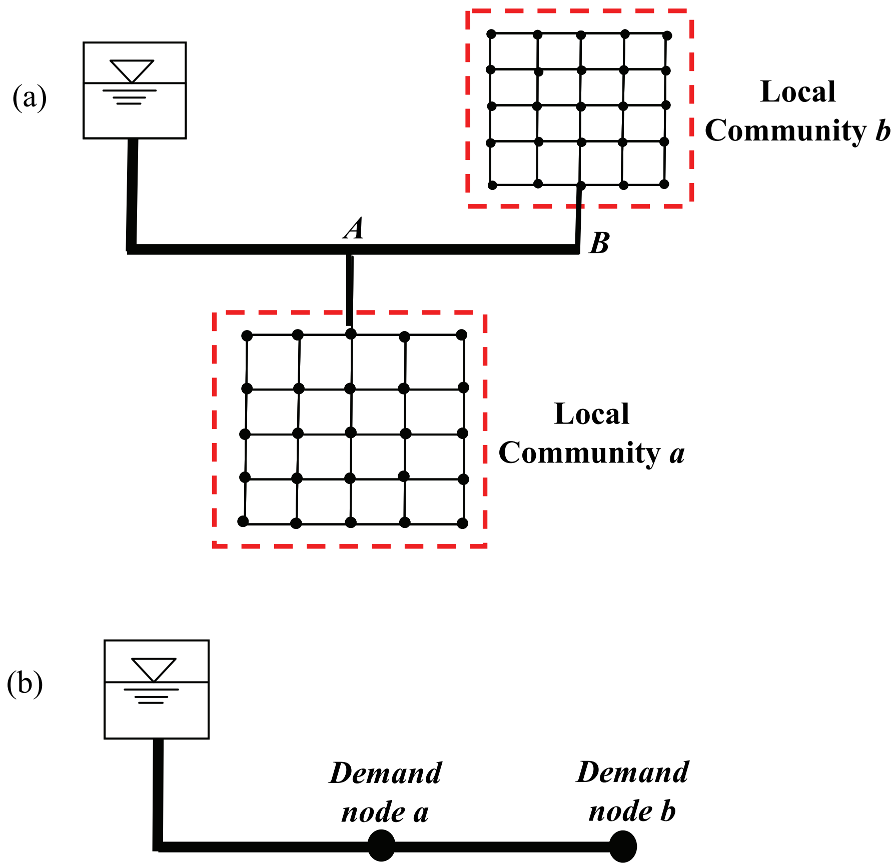


Figure 2.8. Schematic of System (a) with Distribution Lines and (b) with Demand Nodes Representing Distribution Lines (modified from Shi 2006)

2.3.2. GIRAFFE Earthquake Damage and Functionality Estimation Model

A software program called *Graphical Iterative Response Analysis of Flow Following Earthquakes* (GIRAFFE) was developed at Cornell University to estimate earthquake performance of water supply networks (Shi 2006, Wang 2006). Developed as part of the MCEER-LADWP partnership, GIRAFFE estimates damage and functionality for heavily damaged water systems, a circumstance when standard hydraulic analysis models, like H2ONET, do not work. This section describes its key features necessary for understanding its role in the restoration model. Shi (2006) describes the program in detail.

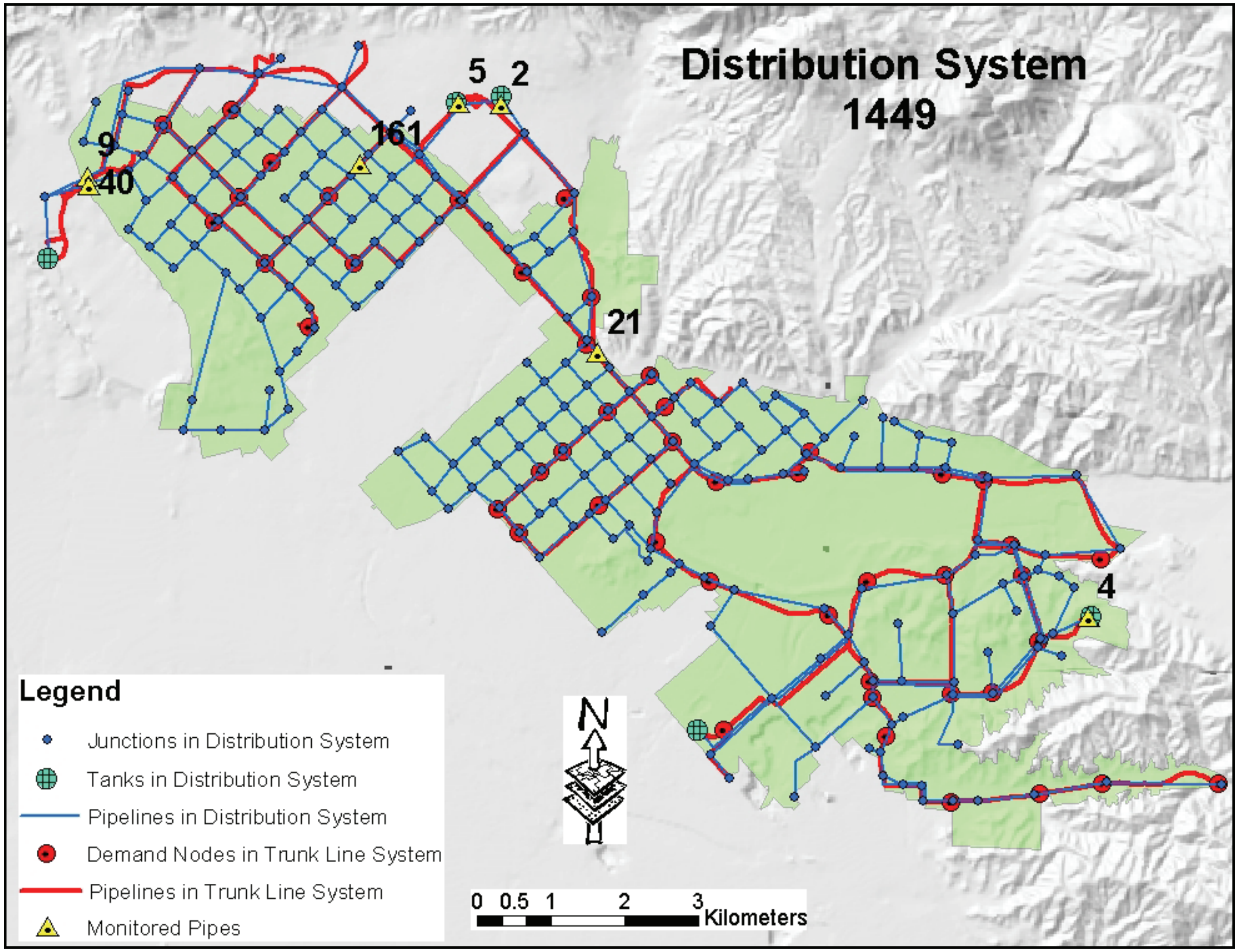


Figure 2.9. Map Showing the Distribution System Hydraulic Network Model for One Area (Source: Shi 2006)

Figure 2.10 summarizes the main steps in GIRAFFE. First, the hydraulic network being analyzed is defined using the graphical user interface from EPANET, a free, standard hydraulic analysis program (Rossman 2000). The system definition includes the topology, physical and operational characteristics of the system, and normal system demands. Trunk lines are represented explicitly as lines in the network model. Distribution lines are represented as demand nodes on the trunk network.

Second, the system is modified to simulate the occurrence of earthquake-caused damage. Damage to trunk lines is represented as distinct breaks and leaks. Trunk line damage can be modeled in two modes: deterministic and probabilistic. In the deterministic mode, the user can specify the locations of breaks and leaks. In the probabilistic mode, given a particular earthquake, the model simulates the occurrence of breaks and leaks according to a Poisson process, where the mean damage rate is a function of the peak ground velocity experienced at the pipe. The probabilistic mode results in multiple realizations of damage. Damage to distribution lines is represented by increasing the demand at the demand node that represents the damaged distribution lines. This reflects the fact that distribution pipes with breaks and leaks in them will draw more water than normal from the trunk line network because the water will be spilling into the ground rather than just serving customers. Damage at a demand node is based on the peak ground velocity and mean pressure at that node. GIRAFFE does not explicitly model the number of breaks and leaks associated with distribution line damage (see Section 3.3). The system definition file is modified to represent the trunk line breaks and leaks and the new demands.

Next, GIRAFFE performs a hydraulic analysis on the modified system using the EPANET engine. In this step, GIRAFFE first checks the connectivity of the modified system and removes any components that are isolated from water sources. It then runs a normal hydraulic analysis. If any nodes are found to have negative pressure, they are removed from the system and the analysis is rerun. This is repeated until there are no nodes with negative pressure. Those results are the final ones.

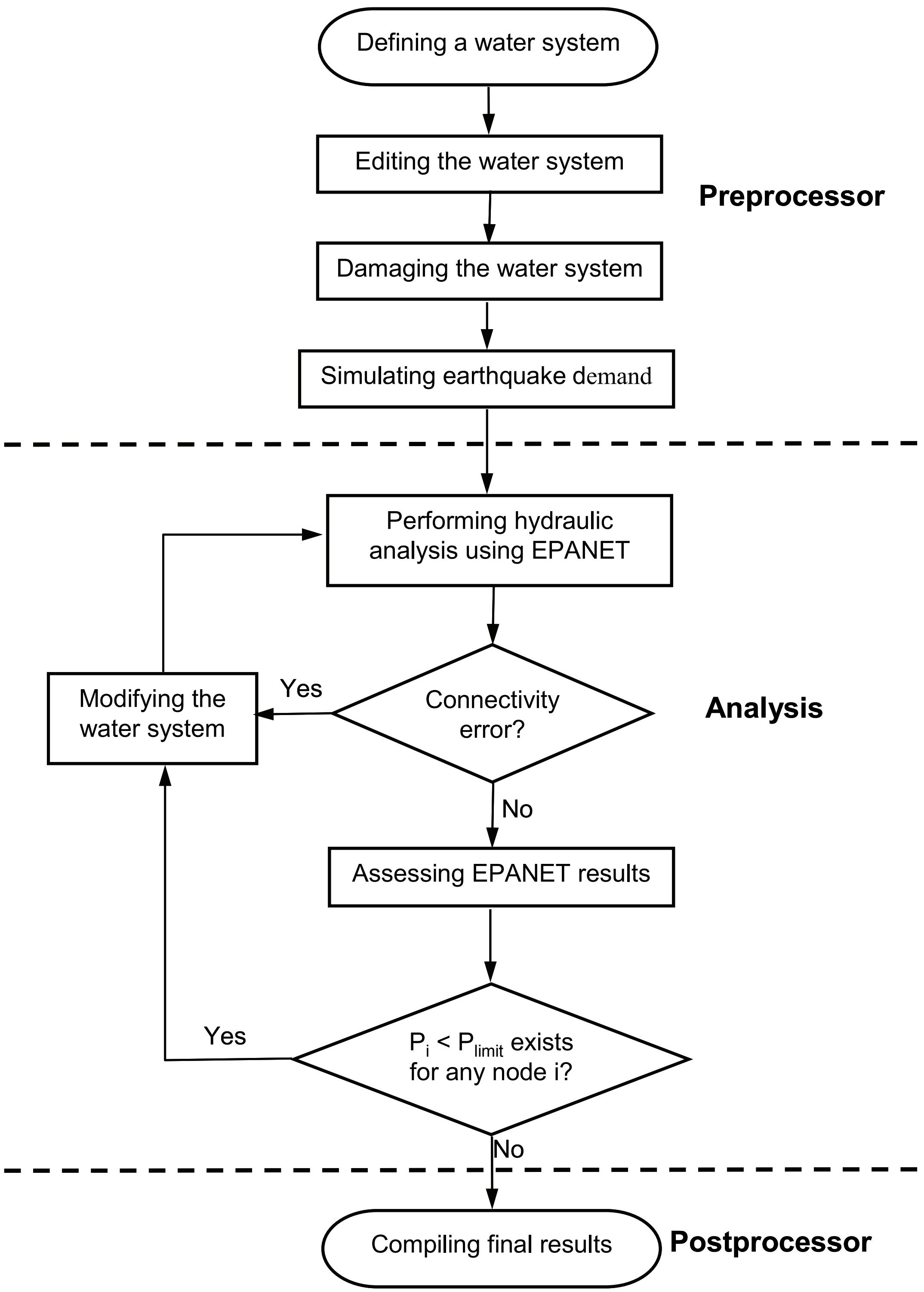


Figure 2.10. Flowchart for GIRAFFE (Source: Shi 2006)

The output from GIRAFFE includes the flow and/or pressure at each system component (e.g., pipe, junction, pump, tank). For each demand node, it indicates whether it is satisfied or not (i.e., whether the trunk network can get water to that node). It also produces the system serviceability index (SSI), which is defined as the ratio of the total available demand at demand nodes after an earthquake to total required demand at demand nodes after an earthquake.

2.4. LADWP Water Organization

The LADWP water supply organization is divided into four main divisions (formerly called business units): Water Distribution (WD), Water Quality and Operations (WQ&O), Water Engineering and Technical Services (WETS), and Water Resources (WR). Each of these divisions has its own set of crews and procedures to be followed in the event of a large earthquake. The information presented in Sections 2.4 to 2.7 is based on interviews with many LADWP personnel and on the Emergency Response Plans for the LADWP WD, WQ&O, and WETS divisions (LADWP WD n.d., LADWP WETS 2001, LADWP WQ&O 2005).

The Water Distribution (WD) division is responsible for the installation and maintenance of water distribution facilities, which includes trunk lines (at least 610 mm (24 in.) in diameter), distribution lines (less than 610 mm (24 in.) in diameter), meters, fire hydrants, regulators, valves, appurtenances, and other related items. This division also designs distribution lines (not trunk lines) and operates valves on the distribution lines (not trunk lines). WD is organized according to the 5 geographic districts: East Valley, West Valley, Western, Central, and Harbor (Figure 2.5). Each district manages its own facilities to a large extent, and each has its own district yard to which personnel reports and in which materials are stored (Harbor has two, Harbor and North) (Figure 2.11). During the restoration process following an earthquake, WD is responsible for the inspection and repair of its facilities.

The Water Quality and Operations (WQ&O) division divides its responsibilities between two main sections: Operations and Maintenance and Water Quality Compliance. The

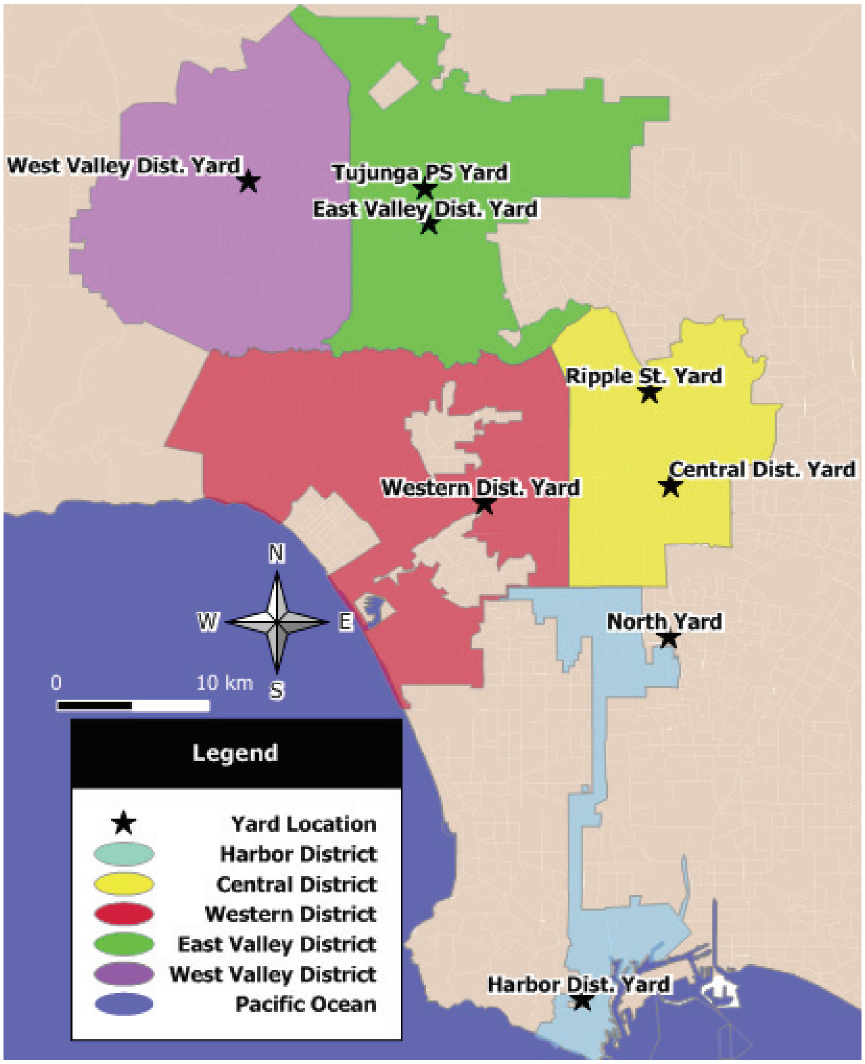


Figure 2.11. WD District Yard and WQ&O Yard Locations

Operations and Maintenance (O&M) Section includes four groups: Transmission Operations, Treatment Operations, Repair and Construction, and Property Management. The O&M Section oversees the operation and maintenance of the filter plants, pump stations, regulator stations, tanks, reservoirs, and ground wells. During the restoration process, this section is in charge of inspecting and repairing these same facilities. The O&M Section also operates the SCADA system, which can remotely monitor levels in tanks, reservoirs, and wells; monitor (and operate some) valves at regulator stations, tanks, and reservoirs; and monitor pressures and flows in some trunk lines. The Water Quality Section works out of the Van Norman Complex and oversees the quality of the water distributed throughout the system. During the restoration process, this section will assist managers in determining whether to issue water purification notices.

Water Engineering and Technical Services (WETS) is a technical division that focuses on the design of facilities for the water system, including trunk lines (but not distribution lines). Staffed largely by engineers and construction managers, it does design and oversees construction and the start-up of facilities, but does not do the actual construction and does not own any of the facilities. During the post-earthquake restoration process, the division's primary duty is to assess the safety of dams and reservoirs in the LADWP service area and to provide technical assistance to the other divisions.

The Water Resources division is responsible for the facilities that deliver water to the LADWP system, e.g., the aqueducts. Since its facilities are not within the service area, it is not considered in development of the restoration model.

2.5. Post-earthquake Restoration Overview

The information presented in Sections 2.5 to 2.7 is based on extensive interviews and conversations with many LADWP water personnel, the LADWP Emergency Response Plan for each major division in the organization, and experiences in the San Fernando and Northridge earthquakes. Although each LADWP division has its own emergency response plan, they primarily establish basic guidelines for who is responsible for what. To provide flexibility, they intentionally do not detail how decisions will be made under different circumstances, but rather allow the people in charge to use their judgment at the time. Further, while each department has an understanding of what to do in the event of an earthquake, few people can provide details about the entire process. As a result, the detailed company-wide restoration process that is expected to unfold following the next earthquake was not documented in one place and required extensive work to develop. It is described in Sections 2.6 and 2.7

Since each earthquake is different and brings unanticipated challenges, the actual restoration process following a future earthquake inevitably will be different than the description provided here. Nevertheless, this is the best available understanding of what will happen, it captures the key features of the process, and it should be reasonably accurate. Further, the restoration model explicitly represents many aspects of the uncertainty in the process (Chapter 3).

The goals that guide the LADWP restoration process are: (1) to restore water service to the most people as quickly as possible, with special consideration given to hospitals, fire fighting needs, and life threatening and other high priority situations; (2) to have a water purification notice for as short a time as possible; (3) to not interrupt water to an area after it has been restored; and (4) to not reinstitute a water purification notice in an area after it has been lifted. Section 2.6 describes the key crews involved in restoration and Section 2.7 outlines the procedure they are expected to follow after an earthquake.

2.6. Restoration Crews

The restoration model described in Chapter 3 follows crews that originate from the WD, WQ&O, and WETS divisions and are directly involved in the restoration process within the LADWP service area. In this section, the principal crews involved in post-earthquake restoration from each division are introduced—what they do, how many and what type of people are on each crew, how many crews there are, where people initially report following an earthquake that occurs during work or non-work hours, how their shifts are organized, how they communicate, and where they get their equipment. Table 2.1 summarizes much of this information. For all types of crews, it is assumed that not all crews will report as they are supposed to immediately after an earthquake, but most of those not there initially will gradually report over the following day or two. For all WD and WQ&O crews, the first post-earthquake shift, which will begin immediately after the earthquake, is likely to be especially long, as it was following the

Northridge earthquake. After the first shift, they will adjust into a schedule of two 12-hour shifts, with approximately ⅔ of all personnel on the day shift and ⅓ on the night shift.

2.6.1. Water Distribution Division Crews

During the restoration process, the Water Distribution division mobilizes (1) inspectors and (2) repair crews. Following an earthquake all employees report to their assigned district yards. If an employee is unable to report to his usual district yard, he may go to another instead. WD crews communicate by 900 MHz 2-way radio or Nextel cell phone. All WD supervisors and all WQ&O personnel have Nextel phones, but some non-supervisor WD personnel may not. Gate Men (Water Utility Specialists), Meter Operators (Meter and Service Crews), and Light-Duty Truck Operators all work as inspectors following an earthquake, and they all work individually. For each district yard, there are 5 Gate Men, 10 to 15 Meter Operators, and 2 to 3 Light-duty Truck Operators. Personnel from district yards in non-damaged areas help as needed. There are approximately 400 construction personnel total in WD who can be called in if necessary. The inspectors are dispatched to examine pipelines and find leaks in areas identified by the Trouble Board it is associated with (see Section 2.7.1 for description of Trouble Boards). They then report their findings back to the Trouble Board. They may also be assigned to operate valves within the system to aid in rerouting water and/or isolating damage. All of their equipment is contained on trucks issued by the department.

Table 2.1. Summary of WD, WQ&O, and WETS Crews Involved in the Post-earthquake Restoration Process

Division	Crew Name	Reporting Location[1]	Size and Number of Crews	Responsibilities
Water Distribution	WD inspectors	Assigned district yard	5 gate men, 10-15 meter inspectors, and 2-3 light-duty truck operators per district. They work individually.	Inspect leaks reported to Trouble Board. Reroute around trunk damage. Isolate distribution damage.
	Repair and Construction Crews	Assigned district yard	Crews of 2 for small repairs and 5 for large projects; some 3-person crews also available. 80 each in Central and Western; 50 each in East Valley, West Valley, and Harbor	Repair damage to pipelines
Water Quality & Operations	Water Utility Operators (WUO)	Ripple St. Yard, Harbor District Yard, or Tujunga PS; or if on-duty inspect current facility, then report	24 people who work individually	Inspect pump stations, tanks, reservoirs, and wells. Reroute around trunk damage. Isolate distribution damage.
	Water Utility Workers (WUW)	Ripple St. Yard, Harbor District Yard, or Tujunga PS; or if on-duty inspect current facility and then report	12 crews of 2	Inspect regulator stations; also tanks and wells left uninspected after regulator stations are all inspected. Reroute around trunk damage. Isolate distribution damage.
	Repair and Construction	Ripple St. Yard or Tujunga PS	20-30 crews of 2-3 each (about 60 people total)	Repair damage to pump stations, regulator stations, and other facilities within WQ&O's responsibilities

[1] JFB is the John Ferraro Building, where LADWP headquarters is; VNC is Van Norman Complex; and PS is pump station

Table 2.1. (Continued)

Division	Crew Name	Reporting Location[1]	Size and Number of Crews	Responsibilities
Water Engineering & Technical Services	Damage Assessment Team (DAT)	JFB, VNC, East Valley District Yard, and Western District Yard	4 crews of 10; 2 of each: electrical, mechanical, structural, trunk line engineers, and field inspectors	Assist WQ&O and WD personnel: (1) assess damage, (2) recommend repairs, and (3) document damage for reimbursement
	Reservoir Inspection Team (RIT)	JFB or VNC; can go to critical reservoirs before reporting in an emergency if directed	13 crews of 2, plus 1 or 2 coordinators	Assess reservoirs in system for safety; provide a more technical evaluation of reservoirs/dams than WQ&O personnel

[1] JFB is the John Ferraro Building, where LADWP headquarters is; VNC is Van Norman Complex; and PS is pump station

Construction crews that do pipe installation and repair in normal times do repair in a post-earthquake situation. West Valley, East Valley, and Harbor district yards have approximately 50 repair personnel each—20 two-person repair crews and 2 five-person repair crews each. Central and Western district yards have approximately 80 repair personnel each—30 two-person repair crews and 4 five-person repair crews each. Two-person crews undertake smaller repair projects; five-person repair crews undertake the larger repair projects.

Repair and construction crews are responsible for repairing pipe damage and restoring service to customers. Assignments are given at the beginning of a shift and repair crews remain in the field during the shift. They will call in for additional assignments if needed. Crews' materials are carried on department-assigned trucks, are stored in the district yard, or can be delivered in the field. Districts that are closest to the heavily damaged areas will deploy all of their personnel during the restoration. Repair and construction crews from non-damaged districts may help relieve crews in the affected districts. Repair crews from other companies that show up are used for small projects, such as repairing leaks in distribution lines. They tend to be less efficient since they are not familiar with the system. Following the Northridge earthquake, 25 crews came from 11 other utilities (McReynolds and Simmons 1995).

2.6.2. Water Quality and Operations Division Crews

Since the primary concern of the restoration model is the time at which customers have their service restored, only the Operations and Maintenance Section of the WQ&O Division is considered (not Water Quality Compliance). The O&M Section includes the following groups: Transmission Operations, Treatment Operations, Repair and Construction, and Property Management. SCADA is operated by 8 employees who rotate in shifts of 1 to 2 people 24 hours per day.

The Transmissions Operations Group includes Water Utility Operators (WUO) and Water Utility Workers (WUW). There are about 24 WUOs who work individually, and about 12 two-person WUW crews. Following an earthquake, the WUOs and WUWs assess the damage and functionality of the facilities, and determine what is needed to repair them. If an earthquake occurs during normal working hours, WUOs and WUWs will inspect the facilities they are at, and then call in to their supervisors to report the results of the inspection. WUOs will then begin inspecting their pre-assigned facilities listed in the Internal Coordination Plan and in the order listed in the WQ&O Emergency Response Plan (ERP). WUWs will report to the Ripple St. Yard or Tujunga Pump Station (PS), as assigned in the WQ&O ERP. If an earthquake occurs during off-duty hours, WUOs and WUWs call an 800 number to get instructions. If the earthquake is at least magnitude 5.0 and within 50 miles of the LA Civic Center, WUOs and WUWs call the 800 number, then their supervisors, then the Los Angeles Water Supply System Data Acquisition Control center (LAWSDAC). LAWSDAC is located in the John Ferraro Building (JFB), where the LADWP headquarters is. If they can not reach anyone, the WUOs report to their pre-assigned locations listed in the WQ&O ERP, and WUWs report to their Field Facility Locations (i.e., their regular reporting locations—Ripple St., Tujunga PS, Encino, Harbor District Yard, and Van Norman Complex).

The Water Utility Operators inspect the 80+ pump stations and about 110 tanks and reservoirs (which are often located near the pump stations). The assignments are divided among the available WUOs, so each will inspect 3 to 4 pump stations and any adjacent tanks and reservoirs. They will also inspect any trunk lines connected to the pump stations. After the pump stations, tanks, and reservoirs have been inspected, the WUOs will be assigned to inspect the 60 to 80 ground wells in use at the time, most of which are in the San Fernando Valley. The Water Utility Workers inspect the 350+ regulator stations (about 30 to 40 regulator stations per crew). The WUOs and WUWs have radios to communicate with headquarters. Materials for WQ&O inspection and repair are stored mostly at the Ripple St. Yard, with some at Tujunga PS. They may request additional assistance from DATs if needed during their inspections. Crews arriving from other companies will not be used to help with WQ&O inspection and repair. (They will only be asked to help with WD facilities.)

Repair and construction crews from WQ&O repair damage to the pump and regulator stations, tanks and reservoirs, and wells. There are about 60 WQ&O repair personnel organized into 20 to 30 crews of 2 to 3 people each. If an earthquake occurs during business hours, they inspect the facility they are at and then call in to report to their supervisor (or LAWSDAC or LAAFP control room if the supervisor is unreachable). If they cannot reach anyone, they report to the nearest of four reporting locations—San Pedro Pump Station, LAAFP, Western District Yard, or Temple St. Yard. If an earthquake occurs during off-duty hours, WQ&O repair crews call an 800 number to get instructions. If the earthquake is at least magnitude 5.0 and within 50 miles of the LA Civic Center, they call the 800 number, then their supervisors, then LAWSDAC. If they can not reach anyone, they report to their pre-assigned locations—Temple St. Yard or LAAFP. The WECC and WQ&O managers determine priorities for repairs and dispatch WQ&O repair crews, who stay in the field during an entire shift. If possible, they report back by radio or phone during the shift; otherwise, they report at the end of the shift.

2.6.3. Water Engineering and Technical Services Division Crews

There are two main types of crews originating from the WETS division that are involved in the restoration process: Damage Assessment Teams (DATs) and Reservoir Inspection Teams (RITs). The DATs serve as technical support for the other divisions in assessing damage to facilities, recommending repairs, and documenting damage. DATs are called in to inspect building damage, for example. RITs are responsible for assessing the damage and safety of the reservoirs and dams in the LADWP system. They conduct more detailed technical evaluations than the initial evaluations conducted by WUOs.

There are 4 DATs, composed of 10 team members each. Each is assigned to a specified geographic area and reports to a specified location (in parentheses): Central (John Ferraro Building, JFB), Los Angeles Aqueduct Filtration Plant (LAAFP, West San Fernando Valley), East Valley (East Valley District Yard), and Western (Western District Yard). Each DAT is composed of two each of the following: trunk line engineer, structural engineer, electrical engineer, mechanical engineer, and field inspector. Immediately after an earthquake, DAT members call an 800 number and a message tells them if their DAT has been activated. If it has, they report to their pre-assigned location—East Valley District Yard, JFB, LAAFP, or Western District Yard—and await further instructions. They are given assignments at the beginning of the day and report back at the end of the day. They have materials or kits available at their reporting locations. Each 10-person DAT may be divided up in order to send a couple people to one location, a few to another location, and so on, depending on what each damaged site needs.

About 26 individuals comprise the RITs, plus 1 or 2 coordinators. There are 13 teams of 2 that work to inspect the safety of the dams and reservoirs within the LADWP system. The pairs are not pre-assigned; rather they are assigned depending on who reports for duty. Following an earthquake that is during normal business hours, RITs are dispatched from the John Ferraro Building (JFB) because that is where they normally work. Following an earthquake that occurs during off-duty hours, RIT personnel will call an 800 number to get an assignment. If it says to report (a Level 2 event as defined in the RIT ERP), they contact the RIT coordinator to get an assignment. If they cannot reach the RIT coordinator, they report to the Van Norman Complex or the JFB, and a few people will inspect assigned reservoirs before reporting. The RIT coordinator will have them follow this plan as well. Materials for inspections are contained at the reservoirs and at reporting locations. RITs communicate using phones, cell phones, pagers, and radios, or if those modes are unavailable, through operating personnel or leaving messages with the WECC.

2.7. Restoration Timeline of Tasks

In this section, the four main phases of the LADWP post-earthquake restoration process—inspection, rerouting around trunk line damage, isolating distribution damage, and repair—are described through discussion of the activities of the crews involved. The description of each phase includes the goals of the phase, the tasks that take place during the phase, how the tasks are prioritized, and the expected duration of the phase and/or tasks it includes.

During inspection, which begins immediately following an earthquake, facilities and pipelines are examined to determine the level of damage and degree of functionality, if there are any safety concerns, and what needs to be done to isolate the damage and repair it. The goals of the rerouting and isolating phases are to minimize water loss, minimize the number of customers without service, and maximize the water available for fire fighting. This is accomplished by opening and closing valves and adjusting settings at regulator and pump stations so as to minimize flow to damaged areas and redirect water to customers through different paths. (Minor rerouting around a damage location as part of a repair is considered part of the repair process). Rerouting and damage isolation occur concurrently with inspection and repair. In the repair phase, damage is repaired so that the facility or pipeline is functional. Repairs may be temporary or permanent. Temporary repairs are assumed to last days or weeks (i.e., beyond when the earthquake event is considered over), but ultimately to require more extensive work. For purposes of modeling the post-earthquake restoration process, temporary repairs are in effect permanent. For each facility or pipeline, the repair phase can begin immediately after inspection is completed.

In water supply systems, unlike other lifelines, one can consider three different types of restoration curves, related to (1) restoration of non-potable water service, (2) restoration of potable water service, and (3) repairs to the system. These three levels of restoration may occur at different times. This study focuses on the first type of restoration. That is, the restoration is considered complete when all customers have service restored. Some facilities and pipelines may still be damaged at that time, but because of temporary repairs or rerouting, all customers nevertheless have service. It is expected that water purification notices will be issued as necessary, so that water can be restored without additional delays due to concerns about water quality. Repair times are estimated under this assumption. Water trucks may be used to provide potable water to customers without service, as they were following the Northridge earthquake (McReynolds and Simmons 1995). This mitigates the detrimental effects of the water supply system being nonfunctional, but does not affect the restoration time of the system, so water trucks are not considered in the simulation model.

The Water Emergency Command Center (WECC) is established in the John Ferraro Building (JFB, LADWP headquarters) within a few hours after an earthquake. Managers from the water system run the WECC, which is responsible for overseeing the restoration process. All divisions report damage and operational status to the WECC managers, who then determine the priorities for repair and the rerouting to be done. A Field Command Center (FCC) is also established at the district yard that is nearest to the most heavily damaged area, but has not suffered significant damage. The WECC and FCC are the two centers from which major operations are directed.

2.7.1. Inspection Phase

For the WD division, the initial inspection phase is expected to last several hours following an earthquake. Each district yard has a Trouble Board that receives calls from customers and LADWP crews reporting water outages and damage to the system. Only the Central District Yard Trouble Board is open 24 hours a day, 7 days a week, so it covers the entire service area when the others are closed. During a post-earthquake situation, all trouble boards may be kept operating for the duration of the event. When a call is received, a job ticket is created that includes the customer's description of the severity of the problem, the customer location, the time, and other related information. Based mostly on those calls, but also pressure readings throughout the system and other relevant information, the Superintendent and Assistant Superintendent prioritize inspections. WD inspectors (Gate Men, Meter and Service Crews, and Light-duty Truck Operators) are dispatched according to that priority list to inspect potentially damaged pipelines. Following the Northridge earthquake, not all damage locations were identified right away. In some cases, if a break upstream caused a pipe to run dry, then a break or leak downstream was not apparent until the upstream portion was repaired or rerouted around and the pipe was filled again. A similar situation is expected to occur in future earthquakes.

At each potential damage site, the inspector visually inspects the area to locate the source of the water leak, determines the severity of the damage/leak (e.g., water is bubbling up, or street is flooded), identifies the size and type of pipeline that is damaged (e.g., 8 in. (203 mm) cast iron main), uses the gate book to locate the valves in the area that can be used to isolate the damage, identifies any priority customers (e.g., hospital) served by the damaged pipeline, and reports that information to the Trouble Board via radio or cell phone. The inspector will typically receive prioritized assignments at the beginning of the shift, call in damage reports after each inspection, and return back to the district yard only at the end of the shift. In unusual circumstances, a DAT could be called to help inspect trunk line damage. If possible, an inspector may begin isolating damage as well, but usually that is part of the repair process. Based largely on lessons learned in the Northridge earthquake, the plan for future earthquakes is that the largest diameter pipelines will be inspected internally rather than taking the usual approach of repairing a leak, filling the pipeline, then draining the pipeline again if another leak downstream becomes apparent. This will help inspectors discover leaks and breaks not apparent from the surface more quickly.

If an earthquake occurs during work hours, Water Utility Operators (WUOs) and Water Utility Workers (WUWs) will inspect the facilities they are at, then report to their supervisors or pre-assigned location. If an earthquake occurs during off-duty hours, they report directly to their supervisors or pre-assigned locations. Supervisors prioritize facilities for inspection based on the priorities listed in the WQ&O ERP, and by giving higher priority to those close to the epicenter that are more likely to be damaged. For WUOs, pump stations, tanks, and reservoirs are inspected first, then ground wells. Crews will typically inspect the facilities they normally work at. During an inspection, a WUO or WUW crew will assess the damage and functionality of the facility and determine what is necessary to repair it. In addition, WUOs and WUWs may be asked to operate valves to prevent further water loss and/or to isolate damage within the system. WUOs and WUWs should have radios to communicate with HQ so that they can stay in the field during their entire shift. It is expected that the inspection of pump stations, regulator stations, tanks, and reservoirs will be complete and reported to the WECC within 8 to 12 hours following the earthquake.

The DATs respond to requests for technical assistance, mainly from WQ&O personnel but possibly from WD personnel as well. They can help assess any facility except reservoirs, which are supported by RITs, and pipelines smaller than 12 in. (305 mm) in diameter. The DATs help to (1) assess a facility's damage, functionality, and safety; (2) recommend repairs; and (3) document damage using the form in the DAT ERP. Damage assessment is expected to occur during the first couple of days and does not take long; recommending repairs may take much longer. Following one or a few assessments, a DAT reports the assessment(s) back to the WECC by using the department-supplied cell phone of a DAT team leader or field personnel (e.g., WUW or WUO), or by driving out of the damaged area and using a pay phone.

If an earthquake occurs during working hours, most RIT members will be dispatched from the JFB where they normally work. If an earthquake occurs during off-duty hours, RIT members report to the location assigned in the RIT ERP—the JFB, the Van Norman Complex, or a specific reservoir. Once at the reservoir to which they are assigned, an RIT determines the safety and functionality of the reservoirs by making a more detailed technical inspection of the reservoir than the WQ&O operator. They then report their findings to the RIT coordinator by radio, cell phone or fax if available, and if not, but driving in to the headquarters. Three vehicles available to the RITs have radios in them. Most of the inspection can be done visually, but having the correct equipment allows them to do a more thorough inspection.

2.7.2. Rerouting Around Trunk Line Damage Phase

The rerouting phase begins immediately following an earthquake to minimize water loss through damaged pipelines, minimize the number of customers without service, and ensure that fire fighters have adequate water. WQ&O and WECC managers decide how to reroute water around trunk line damage. Some valves can be operated remotely from the SCADA system, but most of the rerouting is accomplished by crews in the field (WUOs, WUWs, and WD crews) opening and closing valves, and adjusting settings at pump and regulator stations. Rerouting applies only to trunk lines.

Trunk line damage can take days, weeks, or even months to repair, so before beginning repairs, an effort will be made to reroute water around a damage location so that customers can have their service restored without waiting for the lengthy repair to be completed. There are four main methods of trunk line rerouting, which are, in order of preference: (1) use trunk system redundancy, (2) connect to a Metropolitan Water District (MWD) source (Figure 2.3), (3) connect to a groundwater well (Figure 2.4), or (4) use fire trucks. In the first, preferred method, water is redirected around the damage location using other undamaged trunk lines. It can get water around a damage location within hours, but it is only possible if there is an alternative, undamaged route. Connections to the MWD can be made in a time of emergency provided there is a nearby MWD connection and the MWD supply is functional. This method can also be implemented in a matter of hours. If the first two methods are unavailable and a groundwater well is nearby, the third method is used. As a final alternative, the Fire Department can reroute water around a damaged trunk line from a lower pressure zone to a higher pressure zone by pumping water from one fire hydrant to another. They try to do this by connecting two fire hydrants on the same side of the street, on smaller streets, to minimize traffic disruption. Twenty-five fire trucks were used in this way following the Northridge earthquake, and they expect to do the same in future events. In this manner, the Fire Department can pressurize a whole pressure zone in 2 to 3 days. Using fire trucks is the last option because it requires fire department involvement and takes longer than the other methods.

2.7.3. Isolating Distribution Damage Phase

The goals of isolating distribution damage are the same as those for the rerouting phase. Damage isolation is managed and conducted by the same people who do rerouting, and at the same time. If an area of distribution pipeline is dry (i.e., not currently being served by the trunk system) and heavily damaged, crews may isolate the area from the rest of the system so that it will not cause a great deal of water loss when it is rewetted. The repairs to that area can then be made later after other higher priority repairs are complete. This strategy can succeed in stopping excessive water loss, but all customers within the isolated area will lose service.

2.7.4. Repair Phase

The repair phase can begin at any facility or pipeline once the inspection phase is completed for that facility or pipeline. Each of the divisions is responsible for repairing its own facilities, but they are able to enlist help from other divisions especially from WETS crews. Repair priorities are determined by the managers in the WECC and passed down to the division managers. The priorities are to restore service to areas in which critical facilities are located, like hospitals and schools, and beyond that, to restore service to as many customers as quickly as possible.

The WD division repair crews report to their assigned district yard following an earthquake. They get their truck and repair materials there, and are assigned from one to a few projects at the beginning of a shift. They then remain in the field until all the projects are complete or the shift ends. To minimize crew travel time, projects are assigned by area (say, neighborhood), so that a crew will repair all damage in one area before moving on to another. When mutual aid crews arrive, they will likely be assigned to minor repairs.

To repair a pipeline, a repair crew isolates the damage by operating valves in the area (which are typically separated by 300 ft (91 m) to 500 ft (152 m)); excavates the area around the damage; assesses the damage; puts a repair clamp on the leak or puts in new section of pipe with two mechanical couplings (one on either end); replaces or repairs any broken valves; and tests for water quality (Figures 2.12 and 2.13). Simple repairs for small pipelines take about 2 to 4 hours of work, but can require an additional 2 to 4 hours if a valve is broken as well. Addition or repair of a service connection can also add up to 8 hours to a repair job. Larger main and trunk line repairs require more time, up to a week or two. Major trunk lines typically connect reservoirs, so damage to trunk lines can often be isolated and repaired later.

Figure 2.12. Picture of a Mechanical Coupling from a LADWP District Yard (Source: Çağnan 2005)

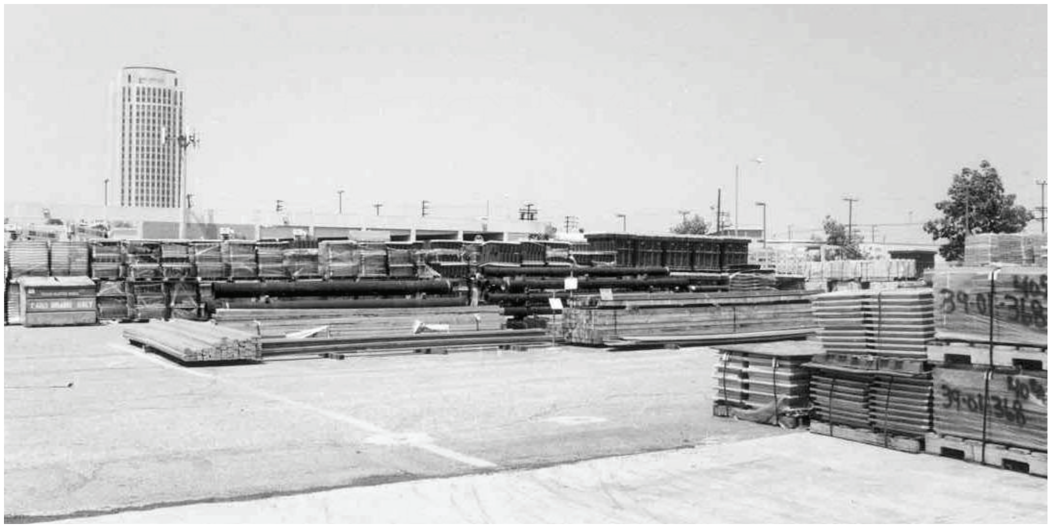


Figure 2.13. Picture of Pipe Sections Stored in a LADWP District Yard

(Source: Çağnan 2005)

WQ&O Repair and Construction crews are responsible for repairs to the pump and regulator stations, tanks, and reservoirs. Unlike pipeline damage, each location of WQ&O facility damage is likely to be unique and may require a long time to repair. As a result, WQ&O facility repairs are managed on a case-by-case basis and may call on many different LADWP personnel to help.

2.8. Summary

The physical system, organization, and post-earthquake restoration process for LADWP water are described in this chapter. Two software models that describe the system and are used in the restoration model—H2ONET and GIRAFFE—are also discussed. The information provided in this chapter forms the basis of the post-earthquake restoration simulation model described in Chapter 3.

CHAPTER 3

POST-EARTHQUAKE LADWP WATER SUPPLY SYSTEM RESTORATION MODEL

3.1. Introduction

The discrete event simulation model of the post-earthquake restoration of the LADWP water supply system is described in this chapter. The purpose of the model is to simulate the real-life restoration process for any input earthquake scenario. It was developed to be as simple as possible, while capturing all the key aspects of the restoration process so as to produce meaningful results. The model is based on the understanding of the real-life LADWP system and planned restoration process described in Chapter 2. The chapter begins with an overview of the model and a summary of the inputs it requires and outputs it generates. The entities, crews, materials, and events that are explicitly represented in the model are then described in Sections 3.5 to 3.12. Chapter 4 describes preliminary calibration of the model to LADWP's experience in the 1994 Northridge earthquake.

3.2. Model Overview

3.2.1. Elements in Model

The key elements in a discrete event simulation are *entities*, *resources*, and *events* (Law and Kelton 2000). Objects of interest in the real system are represented as entities in the simulation model. Each entity has several relevant attributes that describe it. Resources are a special type of entity that can move and provide a service to other entities in the system. Together the entity attributes and other global variables describe the state of the system. Whenever an event occurs, the values of entity attributes and global variables are updated. Simulations are based on keeping track of changes in certain variables as time proceeds (Ross 2002). The one-to-one mapping between objects in the real-life system and their abstractions in the simulation model enables modeling the system under consideration quite accurately without the need to make significant simplifications.

In the LADWP water restoration simulation model, the entities are the physical components of the system (e.g., a piece of trunk line, pump station). A key attribute of each entity is its status, which indicates how far along it is in the restoration process. For example, the possible status values for demand nodes include uninitialized, waiting for inspection resource, being inspected, waiting for isolation resource, being isolated, waiting for repair resource, being repaired, and restored. There are two key types of resources in the model, crews and materials. Each crew also has a status attribute that can take on values that include waiting to go on-duty, traveling, working, idle (not currently needed), or on down time (off-duty). At each time step (time to the next event; can be less than 1 minute to 30 minutes in length), events occur, causing the status of entities and crews involved to be updated. Events that take place within the simulation include inspecting entities, rerouting around trunk line damage, isolating distribution damage, repairing pipe breaks and leaks, and traveling. To determine which specific events will take place in each time step, events are prioritized according to simple rules that reflect LADWP's real-life restoration priorities. As time progresses, the simulation mimics the restoration process quite literally until all customers have water service restored and no more events need to take place. As discussed in Section 2.7, in this model, restoration refers to the non-potable water service.

3.2.2. Interaction with GIRAFFE

At a given time *t*, many decisions about how to prioritize pending events (e.g., which damaged pipe to repair first) depend on both which pipes are damaged and where customers are and are not getting water service at that time. As a result, it is important to know how both the damage and functionality within the system evolve over time. The system damage state is described in terms of trunk breaks and leaks and demand node normalized demands (post-earthquake demand divided by pre-earthquake demand). The system functionality is described in terms of serviceability (Section 2.3.2). For each demand node, serviceability is a binary indicator of whether or not it is being satisfied. For the system (or a region within the system), serviceability is the ratio of total demand available (satisfied) after an earthquake to that required. It is zero if the post-earthquake demand is not satisfied and 1 if it is satisfied.

For the restoration model to base prioritization decisions at time *t* on current serviceability as well as damage, it had to be coupled with the earthquake performance model, GIRAFFE (Section 2.3.2). Figure 3.1 describes the interaction between the restoration model and GIRAFFE. First, GIRAFFE is run in a probabilistic mode to determine multiple realizations of the: (1) initial damage state, and (2) associated initial system serviceability. Each realization of the damage is run in turn. (If GIRAFFE is run in the deterministic mode, only one realization of the initial damage state and system serviceability is used.) For one damage realization, based on the input damage and serviceability, the restoration model repairs some breaks and leaks in trunks and distribution lines during the next time step. The updated damage state of the system is then input back into GIRAFFE, which is run in a deterministic mode to determine the system serviceability associated with that new damage state. This updated damage state includes altering the pipe damage input file and the system definition file. Both files are needed to run GIRAFFE in the deterministic mode. The pipe damage file contains those that were damaged in the initial state of the system that have not been repaired or rerouted. The undamaged system definition file only has the demands altered. When a demand node is not restored or isolated, the

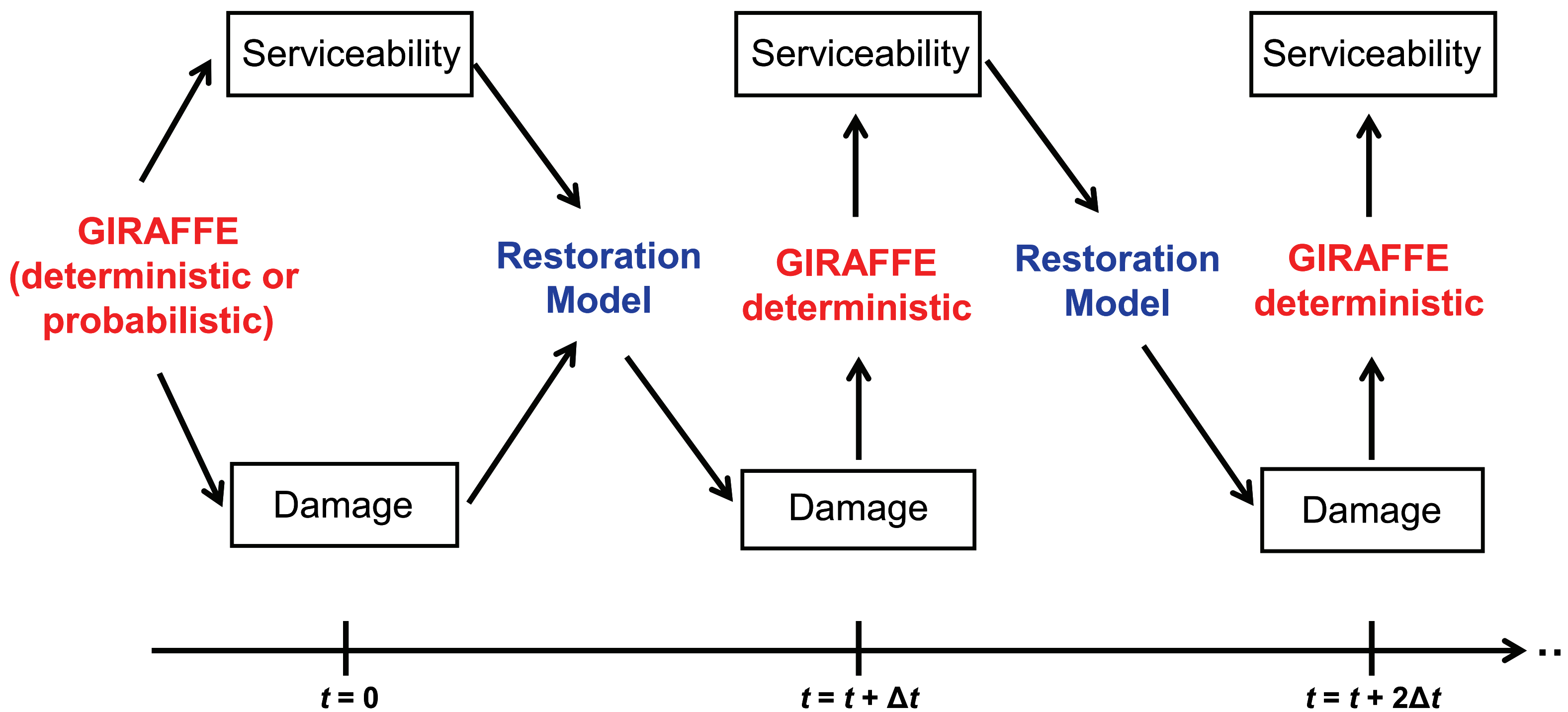


Figure 3.1. Diagram Showing the Restoration Model's Interaction with GIRAFFE

demand is the post-earthquake demand. When it is isolated, the demand is zero, and when it is restored,the demand returns to the node's pre-earthquake value. The revised system damage state and serviceability are then input back into the restoration model, which repairs additional damage locations during the next time step. The process continues until all damage is restored and all customers have water service (i.e., system serviceability equals one).

Each time *t* at which GIRAFFE is called provides one estimate of system serviceability that can be plotted to create a serviceability-versus-time restoration curve (e.g., Figure 4.8). However, calling GIRAFFE takes a significant amount of time, so there is a tradeoff between number of points on the restoration curve and computational demands. In the applications in Chapter 4, GIRAFFE was called at 12-hour intervals for the first 2 days and 24-hour intervals for the remaining 5 days.

The restoration simulation model was programmed in C++ using Visual Studio 2005. C++ was chosen because object-oriented languages lend themselves to use with discrete event simulations, it is flexible language, and GIRAFFE was programmed in C++ as well. Currently, the interaction between the restoration model and GIRAFFE must be accomplished manually. The user must run GIRAFFE, and then run the restoration model, inputting the files produced by GIRAFFE. The user repeats the process several times, manually starting GIRAFFE and the restoration model each time and transferring the necessary files as needed. In the future, it is hoped that the interaction can be automated, perhaps using a Dynamically Linked Library (DLL), so that the user simply runs the restoration model once and the models calls GIRAFFE as part of the run. This would significantly decrease the time required to run simulations.

3.3. Inputs

The restoration model requires a few types of input: (1) system definition, (2) initial system damage and serviceability, (3) location and area definitions, and (4) various user-specified parameter values. The system definition, which is taken from H2ONET and exported to an EPANET file format, describes the components of the hydraulic network being analyzed, i.e., the LADWP water system. It includes locations and key attributes for each entity (e.g., trunk line location, size, and capacity). Multiple realizations of the initial post-earthquake damage and serviceability of the system can be obtained from an initial run of GIRAFFE using the "Monte Carlo Simulation" option (Section 2.3.2). Each realization of the damage includes the numbers of breaks and leaks on each length of trunk line and the post-earthquake demand at each demand node. If the distribution pipelines represented by a particular demand node are damaged, then the post-earthquake demand for that node will be greater than its pre-earthquake demand because the breaks and leaks mean that those distribution pipes are drawing more water than normal from the trunk line network. For each realization of damage, GIRAFFE also provides a corresponding description of serviceability that indicates whether or not each demand node is being served (i.e., whether water is getting through the trunk network to the distribution pipes represented by that node).

Several locations and areas have to be input as well. For locations, coordinates are specified; for areas, the relevant entities they contain are specified. The locations of each district yard are required so that the model knows where crews are dispatched from and report back to. The locations of the earthquake epicenter and the sources for the water system are used for some task prioritization rules (Section 3.8 to 3.12). For example, facilities closer to the epicenter will be inspected first, representing the idea that LADWP will first try to inspect facilities that are most likely to be damaged. The major water sources for the LADWP system are defined to be the Van Norman Complex, the Eagle Rock Reservoir, and LA-21 and LA-16 MWD connections in the Harbor district (Figure 3.2). Additionally, in the summer LADWP uses water from its ground wells and these sources become important in emergency situations. Because the restoration simulations are run with the H2ONET summer scenario the Manhattan Wells, Rinaldi-Toluca Wells, 99th Street Wells, North Hollywood Wells, Tujunga Wells, and Mission Wells are also considered water sources for the LADWP system (Figure 3.2). If MWD connections or wells are used during a rerouting operation, those locations are then added to the list of water sources. Facility repairs tend to begin at a water source and move outwards.

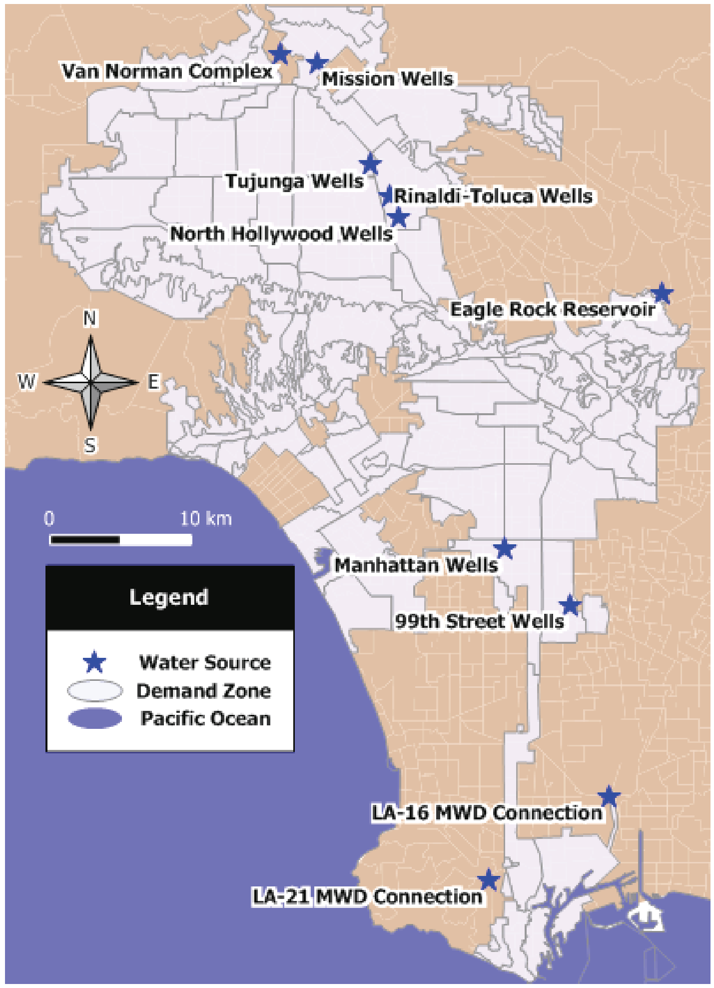


Figure 3.2. Water Sources within the LADWP System

Geographic zones, called "Demand Zones," are also defined for use in prioritizing tasks. The zones correspond to the LADWP pressure zones (Section 2.2, Figure 2.7), with larger zones divided by major highways or roads (Figure 3.3). There are 169 Demand Zones and 106 pressure zones. To minimize travel time, water distribution crews will focus on restoring water to one area completely before moving to another. These Demand Zones are used to model this and to ensure that crews are not asked to travel far distances between jobs.

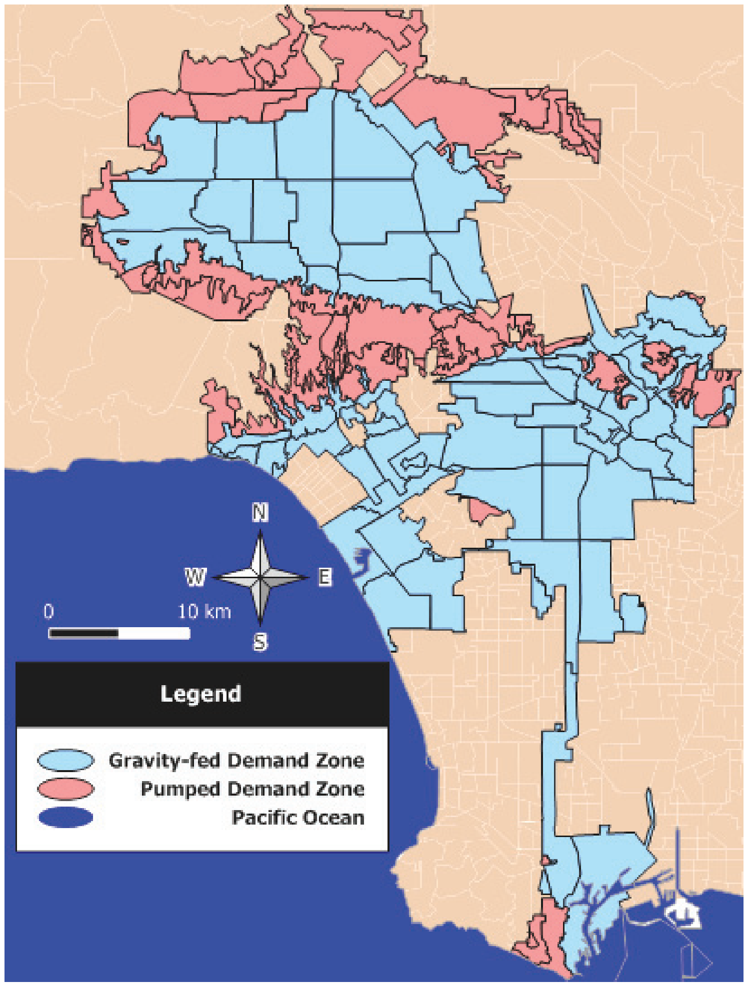


**Figure 3.3. Demand Zones used for the Restoration Model.
The original pressure zones in the LADWP service area were used,
and the larger zones were split using major
roads and highways.**

Finally, there are several parameter values that the user must specify, such as, probability that a distribution line damage location is a break rather than a leak, threshold of distribution damage that indicates if the demand node will be isolated, triangular distribution for travel speed, large user and hospital factors, and time period between runs of GIRAFFE.

3.4. Outputs

This restoration simulation model can produce several different types of outputs. As mentioned in Section 3.2.2, GIRAFFE is used to produce multiple realizations of water system damage given a particular earthquake. The restoration model is run for all those realizations and results can be obtained for each earthquake-damage state combination separately, or by combining the results for all damage state realizations, a single set of results can be obtained for one earthquake. The model collects the following output for a single input earthquake-damage state combination:

a. **Serviceability at *t***. System and Demand Zone serviceability (percentage of demand met) at specified times *t*, estimated from GIRAFFE runs (Section 3.2.2). By default, *t* is taken at 12-hour intervals from 0 to 2 days after the earthquake, 24-hour intervals 2 to 6 days after, and 48-hours intervals for the remaining restoration time.
b. **Restoration curves**. Curves showing serviceability versus time for the system as a whole and each Demand Zone, including 90% confidence intervals that capture uncertainty in the restoration process. These are developed using the data in Item *a*.
c. **Average time without water**. The area above a restoration curve, which is equivalent to the average time each customer is without water, provides a useful scalar summary of restoration efficiency.
d. **Restoration times**. Time required to restore the system and each Demand Zone to 90, 98, and 100% serviceability. Time required to restore each demand node is also provided.
e. **Spatial distribution of restoration**. Demand Zone serviceability data from Item *a* or demand node restoration time data from Item *d* can be mapped to show the spatial evolution of the restoration process.
f. **Crew usage**. Total time idle, traveling, and working for each type of crew, by reporting location.

g. **Material usage**. Number of materials used during each 12-hour period, by district yard and material type.

By combining the output from all the realizations of damage associated with a single earthquake, the model can also include damage uncertainty in the 90% confidence intervals for the restoration curves and system, Demand Zone, and demand node restoration times.

3.5. Entities

The entities included in the LADWP water supply system restoration model are: trunk lines (major and minor), demand nodes (representing the distribution pipelines), tanks, reservoirs, regulator stations, pump stations, and wells. Each of these components is represented within LADWP's hydraulic network model H2ONET (see Section 2.3.1) and in the damage model, GIRAFFE (see Section 3.2.2). Table 3.1 summarizes some of the main attributes for each type of entity. The damage locations

Table 3.1. Summary of Main Entities within the Restoration Model and their Attributes
(The name of the entity's class within the model is indicated in parentheses.)

Entity	Attributes
Trunk line ("Pipe_Entity")	ID Number of breaks Number of leaks Distance from earthquake epicenter Distance to nearest water source Inspection, isolation, and repair priorities Demand zone assignment District yard assignment Current phase in the restoration Type, major or minor Node IDs Node X and Y-coordinates Rerouting method Inspection time Rerouting time Repair time
Demand Zone ("DemandZone")	ID Number of demand nodes Number of demand nodes without service Zone serviceability Total number of breaks Total number of leaks Distance from earthquake epicenter Distance to nearest water source District yard assignment Inspection, isolation, and repair priorities Current phase in the restoration Centroid X and Y-coordinates Number of hospitals, large users, and customers Average customers restored per hour Number of mechanical couplings, pipe sections, and repair clamps Total inspection, isolation, and repair times
Demand node ("DemandNode")	ID Pre- and post-earthquake demand Number of breaks and leaks Distance from earthquake epicenter Distance to nearest water source Customers restored per hour Inspection, isolation, and repair priorities Demand zone assignment District yard assignment Current phase in the restoration Amount of pipe length Repair rate X and Y-coordinates Inspection, isolation, and repair times Number of mechanical couplings, pipe sections, and repair clamps

Table 3.1. (Continued)

Entity	Attributes
Reservoir ("Reservoir")	ID Distance from earthquake epicenter District yard assignment Inspection priority Current phase in the restoration X and Y-coordinates Inspection time
Tank ("Tank")	ID Distance from earthquake epicenter District yard assignment Inspection priority Current phase in the restoration X and Y-coordinates Inspection time
Pump station ("PumpStation")	ID Distance from earthquake epicenter District yard assignment Inspection priority Current phase in the restoration X and Y-coordinates Inspection time
Regulator station ("RegStation")	ID Distance from earthquake epicenter District yard assignment Inspection priority Current phase in the restoration X and Y-coordinates Inspection time

at the trunk line and demand node entities are modeled individually. Each damage location has a status, and if an entity has multiple damage locations, the entity cannot advance to the next status unless all of its damage locations have reached or advanced past that status. For example, a trunk line entity cannot advance to status 1 (waiting for inspection resource to arrive) unless all of its damage locations have been discovered and inspection entities are enroute. An entity's status is repeatedly updated throughout the simulation. It must begin with inspection before it can continue to rerouting, isolation, or repair. All possible status values for the entities can be found in Table 3.2.

Table 3.2. Restoration Model Entities and Resources with their Possible Status Values
(Entities with multiple damage locations (trunk lines and demand nodes) will not advance their status until all of that entity's damage locations have reached or advanced beyond that status. Similarly for Demand Zones, the status of the zone does not advance until all of its demand nodes have reached or advanced beyond that status.)

Entity/Resource	Status Values
Trunk lines	0 – Uninitialized, damage location has not been discovered or inspection resource not assigned to it yet. 1 – Waiting for inspection resource to arrive 2 – Inspection in progress 3 – Waiting for repair resource 4 – Repair in progress 5 – Repair in progress, waiting for another repair resource to continue work 6 – Waiting for rerouting resource 7 – Rerouting operation in progress 9 – Entity restored, all damage locations are repaired
Demand Nodes and Demand Zones	0 – Uninitialized, damage location has not been discovered or inspection resource not assigned to it yet. 1 – Waiting for inspection resource to arrive 2 – Inspection in progress 3 – Waiting for repair resource 4 – Repair in progress 5 – Repair in progress, waiting for another repair resource to continue work 6 – Waiting for isolation resource 7 – Isolation operation in progress 8 – Entity is isolated 9 – Entity restored, all damage locations are repaired
Reservoirs, Tanks, Pump Stations, and Regulator Stations	0 – Uninitialized, waiting for available inspection resource 1 – Waiting for inspection resource to arrive 2 – Inspection in progress 9 – Entity restored, inspection is completed
WD and WQ&O Inspectors	0 – Idle, currently not needed 1 – Traveling 2 – Working, inspection at entity damage location 3 – Off-duty, on down time 4 – Working, rerouting or isolating at entity or entity damage location 5 – Unavailable following earthquake, not on-duty yet
WD Repair Crews	0 – Idle, currently not needed 1 – Traveling 2 – Working, repair at entity damage location 3 – Off-duty, on down time 5 – Unavailable following earthquake, not on-duty yet

Although the model includes all the entities that are included in H2ONET, only trunk lines and distribution lines (i.e., demand nodes) can be damaged because GIRAFFE only initially modeled pipeline damage. At the time the restoration model was created, damage information for the other facilities was not available. The other facilities (e.g., tanks, regulator stations) are inspected, but then are assumed to be undamaged and operational following an earthquake. This is considered a reasonable assumption because the majority of damage occurs in the pipelines. Fragility curves for the other facilities have been developed for GIRAFFE, and this information can be included in future versions of the restoration model.

As discussed in Section 2.3.2, GIRAFFE provides trunk line damage information in terms of the numbers of breaks and leaks in each length of pipe, and distribution damage in terms of increased demand at the associated demand node. To simulate the time required for inspection and repairs, it is necessary to have distribution line damage in terms of numbers of breaks and leaks as well. To do this, the restoration model applies the same method used to simulate damage to the trunk lines within GIRAFFE (Shi 2006). First, the approximate length of distribution pipe and repair rate *RR* (number of repairs required, i.e., damage locations per unit length) associated with each demand node were obtained from LADWP and Wang (2006), respectively. Using the repair rate and length of pipeline associated with a demand node, a Poisson process, in which the repair rate acts as the mean arrival rate, is used to estimate the number of damage locations (breaks and leaks) associated with that node (Shi 2006). The interarrival distance between damage locations, L, is assumed to follow an exponential distribution and can be simulated using the following equation:

$$L = -\ln(u)/RR \qquad (3.1)$$

where u is a random variable that is uniformly distributed between 0 and 1. To determine the total number of damage locations associated with a demand node, values of the interarrival distance L are generated repeatedly until the cumulative length exceeds the total length of pipe associated with that demand node. Each damage location is then characterized as a break or a leak by comparing another sampled *u* value to the user-specified conditional probability of a break given a damage location. For this project, it was assumed that 5% of damage locations are breaks. The numbers of breaks and leaks for each demand node are estimated at the beginning of each simulation.

3.6. Crews

3.6.1. Crew Types

The several types of crews included in the restoration model are listed in Table 3.3. It is assumed that these crews can perform only the duties indicated in Table 3.3.

Table 3.3. Summary of WD and WQ&O Crews Considered in the Restoration Model

Crew Type	Number by Reporting Location	Tasks
Water Distribution inspection crew	20 per District Yard	Inspect all pipes; isolate; reroute
Water Distribution 2-person repair crew	Central District Yard: 30 Western District Yard: 30 East Valley District Yard: 20 West Valley District Yard: 20 Harbor District Yard: 20 Non-LADWP crews: 25	Repair distribution pipes
Water Distribution 5-person repair crew	Central District Yard: 4 Western District Yard: 4 East Valley District Yard: 2 West Valley District Yard: 2 Harbor District Yard: 2	Repair trunk lines
Water Utility Operators (WUOs)	Tujunga Pump Station: 11 Ripple St. Yard: 11 Harbor District Yard: 2	Inspect pump stations, tanks, small reservoirs, wells; isolate; reroute
Water Utility Worker crews (WUWs)	Tujunga Pump Station: 5 Ripple St. Yard: 5 Harbor District Yard: 2	Inspect regulator stations; isolate; reroute

Note that the Water Engineering and Technical Services (WETS) division crews—Reservoir Inspection Teams (RITs) and Damage Assessment Teams (DATs), though providing an important role in the real-life process, are not expected to significantly impact the time required to restore water service to LADWP customers, so they are not included. Further, because it is assumed that WQ&O facilities (e.g., tanks, reservoirs, pump stations, regulator stations) will not be damaged (Section 3.5), WQ&O repair crews are not included either. If damage information for those facilities becomes available, WQ&O repair crews could be added.

3.6.2. Reporting

As in real life, in the model there is uncertainty in the number of crews that will be available immediately following an earthquake. All on-duty personnel are likely to be available immediately following an earthquake, but off-duty personnel may have difficulty reporting if, for example, the roads are damaged or they have suffered personal injury. To capture this, it is assumed that the percentage of crews available immediately after an earthquake is a random number sampled value from a triangular distribution with minimum, mode, and maximum values of 25%, 50%, and 75%, respectively. It is further assumed that the number of crews available increases linearly until all crews are available 48 hours after the earthquake.

3.6.3. Shifts

The length of the first shift for LADWP crews is expected to be especially long, lasting approximately 24 to 36 hours. After that first shift, the crews adjust to night and day shifts. This is modeled explicitly within the restoration model. It is assumed that the day shift is 8am-8pm and the night shift is 8pm-8am. A random number is sampled from a uniform distribution (0, 24) to determine the hour in which the earthquake occurs. If the earthquake occurs between 8am and 8pm, then the first shift will last until 8pm the next day. Similarly, if the earthquake occurs 8pm to 8am, the first shift will end at 8am the following day. After the first shift, the crews are divided so that 2/3 work the day shift and 1/3 work the night shift.

3.6.4. Scheduling

When a crew becomes available, it is assigned to the next location or entity on a relevant priority list, as described in Section 3.8. As in the real-life process, the crew travels from one location to another instead of traveling back to its reporting location between jobs. Entities can only request resources that are working within the same Demand Zone, or if none of those are available, resources that report to the same district yard. This is to prevent crews from traveling long distances and to leave more time for tasks to be completed. During any shift, a resource can complete a number of different tasks. For inspection and isolating tasks, a crew will not be dispatched unless there is sufficient time to complete the next task before the shift ends. Repair and rerouting tasks that take longer can span multiple shifts.

3.7. Materials

During the restoration process following the 1994 Northridge earthquake, LADWP did not run out of repair materials (or at least not in a way that made a noticeable impact on the restoration process). When materials from the nearest district yard were exhausted, others were moved from yards in farther, undamaged districts, and additional materials were acquired from suppliers within 24 hours. Nevertheless, it is still possible that LADWP could exhaust its supply in a larger earthquake, and in any case, it is useful to know how many are likely to be used so that they can be stockpiled efficiently.

The restoration model keeps track of the amount of each type of pipe repair material used during each 12-hour period, by district yard. Materials are added to the running tally at the beginning of a repair task because it is assumed the task cannot begin without the appropriate resources. The materials monitored are: mechanical couplings, pipe sections, repair clamps, and fire trucks (used for trunk line rerouting operations). While the model does not distinguish particular sizes and material types, the couplings, pipe sections, and repair clamps are tracked separately for distribution pipes and trunk lines. It is assumed that two mechanical couplings and one pipe section are needed for each pipe break, one repair clamp is needed for each pipe leak, and one fire truck is needed for each trunk line rerouting operation. Note that more fire trucks were used per rerouting operation in Northridge, but this allows the model to keep track of the number of trunk rerouting operations that use fire trucks.

3.8. Events Overview

Several types of events occur within the restoration model (Table 3.4). The main types of events correspond to the four main phases of the restoration process: inspection, rerouting around trunk line damage, isolating distribution damage, and repair. Chapter 2 describes what occurs during each of these events in more detail. Traveling and waiting for a next task are additional events that are modeled. Events are completed when an entity or resource changes status.

To determine the order in which events occur, pending events are ordered in priority lists. There are separate priority lists for inspection of each entity type, isolation of distribution damage, rerouting around trunk damage, repair of trunk damage, and repair of distribution damage. In each time step, the simulation loops through each priority list. For each list, if an appropriate type of crew is available, it is assigned to the next event on that list. Because some types of events compete for the same resources (Table 3.3, e.g., rerouting and isolation can both use WUWs), the order in which priority lists are checked within a time step is also important for determining which events happen first. In this model, the order in which priority lists are checked within a time step are, from first to last: trunk line inspection, demand node (distribution pipe) inspection, reservoir inspection, tank inspection, pump station inspection, regulator station inspection, trunk rerouting, demand node isolation, trunk repair, and finally, demand node repair. The model first checks if there are any trunk line damage locations that need to be inspected. If there are, and if a WD inspector crew is available, then that crew is assigned to inspect the first trunk damage location on the priority list. The status of the damage location and the crew are updated, and the model looks for the next item on that priority list. When there are no more items on the trunk line damage inspection list, it begins checking the demand node inspection list, and so on. Note that entities requesting rerouting, isolation, or inspection may draw from the same pool of resources because WD Inspectors, WUWs, and WUOs all perform these tasks. The crews are dispatched on a first come, first served basis.

Table 3.4. Values Defining Event Duration Triangular Distributions

Event		Min.[1]	Mode	Max.
Inspect a	Trunk or distribution damage location	0.5 hr	0.5 hr	1 hr
	Pump station	1 hr	1 hr	2 hr
	Regulator station	1 hr	1 hr	2 hr
	Tank	1 hr	1 hr	2 hr
	Small reservoir	2 hr	2 hr	3 hr
Rerouting operation on a trunk line by	Trunk redundancy (major) [2]	Varies	varies	varies
	Trunk redundancy (minor)	3 hr	4 hr	8 hr
	Connecting to MWD line (varies) [2]	3 hr 4 hr	6 hr	12 hr 8 hr
	Connecting to well (varies)[2]	4 hr 6 hr	6 hr 8 hr	8 hr 12 hr
	Using a fire truck (varies) [2]	1 d 2 d	2 d 3 d	3 d 4d
Isolate distribution damage at 1 demand node		1 hr	2 hr	4 hr
Repair a	Distribution leak	3 hr	4 hr	6 hr
	Distribution break	4 hr	6 hr	12 hr
	Trunk leak	4 d	4 d	6 d
	Trunk break	6 d	8 d	10 d
Travel a distance *D* (km)		*D*/25 hr	*D*/40 hr	*D*/80 hr

[1] hr = hour, d = day
[2] See Appendix A for values for each trunk line

At the beginning of each shift, all priorities are reevaluated and each priority list is reordered according to these new priorities. This represents the reality that information on the status of the system is repeatedly updated as the restoration process evolves, and managers may reevaluate their priorities based on that new information.

All event durations are modeled as triangularly-distributed random variables, a different value is sampled for each instance of the event (e.g., each trunk line inspection takes a different amount of time), and the values for a particular run are sampled at the beginning of the simulation. With the exception of travel time, the values that define the event duration distributions were all elicited during interviews with relevant LADWP personnel based on their experience (Table 3.4). The distribution representing travel speed was assumed by the investigator to account for uncertainty in possible damage to or congestion in the transportation system, and different routes. For simplicity, instead of trying to determine the exact path that a crew will travel, straight-line distances are used and the speeds were reduced to adjust for the underestimation of distance. Task durations for major trunk line rerouting operations vary by specific trunk line (Appendix A).

3.9. Inspection

The first phase of the restoration process is inspection. WQ&O managers identified some facilities that probably will not be inspected, for example, those not currently in service. It is assumed that all other tank, reservoir, pump station, and regulator station entities are inspected if they are within a specified distance of the epicenter (25 km (15.5 mi.) in the analyses in Chapter 4). Wells are rarely damaged and difficult to inspect, so they are not inspected. For pipelines, only identified damage locations are inspected, not the entire length of pipeline within the system. Not all pipe damage locations are discovered and reported to the Trouble Board immediately following the earthquake (Section 2.7.1). If a break upstream causes a pipe to run dry, then a break or leak downstream will not be apparent until the upstream portion is repaired or rerouted around and the pipe is filled again. Therefore, it is assumed that a percentage of the total number of pipe damage locations is discovered during each 12-hour period for the first 72 hours of the restoration effort. The percentages, estimated by LADWP personnel, vary based on type of pipeline and time period (Table 3.5). Trunk line damage is more visible, so most breaks and leaks can be discovered immediately. Distribution line damage can be more difficult to find, and most damage locations are reported to the Trouble Board by customers. At the beginning of the simulation, for each trunk line entity and demand node damage location, a random value is sampled from a uniform distribution U(0,1), and the 12-hour discovery time period is determined based on the appropriate distribution in Table 3.5. A second uniformly distributed random number is then sampled to determine exactly when during the 12-hour period the damage is discovered.

Inspection of pipeline damage locations is prioritized based on straight-line distance to the earthquake epicenter (an indicator of damage), with higher priority for those locations closer to the epicenter. Trunk line and distribution line break and leaks are not distinguished from one another, as an inspector does not necessarily know the extent of the damage prior to arriving at the location. Priorities for tanks, reservoirs, pump stations, regulator stations are also based on proximity to the earthquake epicenter.

Table 3.5. Percentages of Pipe Damage Discovered by Post-earthquake Time (in hours) Period *T*

	Immediately post-EQ	$0<T\leq 12$	$12<T\leq 24$	$24<T\leq 36$	$36<T\leq 48$	$48<T\leq 60$	$60<T\leq 72$
Distribution lines	0.00	0.67	0.07	0.07	0.07	0.07	0.05
Trunk lines	0.90	0.01	0.01	0.04	0.04	0	0

WD inspector crews inspect pipeline damage locations, WUO crews inspect reservoirs, tanks, and pump stations, and WUW crews inspect regulator stations. All crews work within their assigned district(s). WD crews work in the district of the district yard they are assigned to—East Valley, West Valley, Central, Western, or Harbor. WQ&O crews reporting to Tujunga, Ripple St., and Harbor work in East Valley and West Valley, Central and Western, and Harbor, respectively.

3.10. Rerouting Around Trunk Line Damage

The rerouting phase applies to minor and major trunk lines, and it can begin for a particular entity once that entity has been inspected. It is assumed that all damage locations occurring in minor trunk lines (Figures 2.3 and 2.5) can be rerouted around using the trunk line redundancy method. For damage on major trunk lines, LADWP uses four different methods, listed in order of preference: (1) use trunk line redundancy, (2) connect to a MWD line, (3) connect to a well, and (4) use fire trucks. As discussed in Section 2.7.2, not all of these methods are available for every major trunk line. (Appendix A indicates which of the four methods are possible for each major trunk line.) In addition, it is assumed that there is a 75% chance that trunk line redundancy and MWD connection methods will not work in each particular instance even if it is theoretically possible. This represents the idea that other trunk and MWD lines may have been damaged in the earthquake too, making the method infeasible. In the restoration model, for each damaged trunk entity, each of the four remaining methods is tried in turn, in the order listed, and the first method available is used for the rerouting operation. Methods 2 and 3 result in another source being added to the water sources list for the system. If no rerouting method is available, the entity is added to the to-be-repaired list. WQ&O managers provided information on what rerouting methods are likely to be available for each of the major trunk lines.

Rerouting tasks are prioritized in the following order: major trunk breaks, minor trunk breaks, major trunk leaks, then minor trunk leaks. Within each of those categories, priority goes to the entity that is closest to a water source. Distance to water source is used to capture the idea that rerouting and repairs are typically done starting with areas that are in service then working downstream, so that when a section of pipe is restored, water will be available to fill it. The straight-line distances to nearest water source for each pipe and demand node entity are recalculated at each shift change to account for changes in the systems' water sources list.

3.11. Isolating Distribution Damage

For a particular demand node, the isolation of damage (if it is going to happen) can begin once the inspection for that node is complete. A demand node will only be isolated if the distribution damage associated with it is severe. The normalized demand ratio (*ND*=post-earthquake demand divided by pre-earthquake demand) output by GIRAFFE is used as a measure of damage. It is assumed that a demand node will be isolated if the demand is not being met at that particular node and its normalized demand ratio is at least a user-specified value (a default value of 3.0 was used in the analyses in Chapter 4). If it is determined that a demand node will be isolated, then the demand at the node is set to zero and the node is added to the to-be-repaired list, but it is given the lowest priority because it has been isolated. More heavily damaged areas require more time and resources to repair, so they are addressed later in the restoration process.

The WD inspectors, WUOs, and WUWs that are conducting inspections and rerouting trunk lines also do the distribution damage isolation. As mentioned in Section 3.8, requests to isolate distribution damage are given lower priority than requests to reroute around trunk line damage. Among requests to isolate demand nodes, those that are closer to a water source are given higher priority.

3.12. Repair

A trunk line can be repaired once it has been inspected, and a demand node can be repaired after it has been inspected (and possibly isolated). Repair of trunk lines and distribution lines require different types of crews. Two 5-person WD repair crews are sent to each trunk with a break location and one 5-person WD repair crew is sent to each trunk leak location. One 2-person WD repair crew is sent to each instance of damage located at the demand nodes.

Trunk breaks have higher priority than trunk leaks. Among trunk breaks, straight-line distance to the nearest water source determines priority, with closest getting the highest priority. The same is true for trunk leaks.

In the real-life process, to minimize crew travel time, WD managers dispatch distribution repair crews so as to repair all the damage in one neighborhood before moving on to the next area. To represent this strategy in the restoration model, priority for repairing distribution line damage is based first on Demand Zone (Section 3.3, Figure 3.3) and then demand node. The Demand Zones are prioritized based on the estimated *average number of customers restored per* *hour, C_z*. Within each zone, the demand nodes are prioritized based on *customers restored per hour, C_n*. They are calculated as:

$$C_n = \frac{x_n \cdot S_n}{T_n} \tag{3.2}$$

$$C_z = \frac{\sum_{n=1}^{N_z} \frac{x_n S_n}{T_n}}{N_z} = \frac{\sum_{n=1}^{N_z} C_n}{N_z} \tag{3.3}$$

where x_n is the number of customers served by demand node n, S_n is indicator variable equal to 1 if node n is satisfied and 0 otherwise, T_n is the estimated time required to repair all breaks and leaks at node n, and N_z is the number of demand nodes in Demand Zone z. Higher values of C_z and C_n correspond to higher priority for repair. This accounts for the LADWP goal to restore as many customers in the shortest amount of time during an emergency. For each demand node n, the value of S_n may change during the simulation as the damage is gradually repaired and demand nodes that originally were not satisfied become satisfied. For each node, the time required to repair all breaks and leaks, T_n, is calculated by sampling repair times for each damage location using the distribution described in Table 3.4, then summing those values.

The number of customers served by each demand node, x_n, is an input quantity. To reflect the idea that areas with critical care facilities receive higher priority during the restoration process, if one or more hospitals are served by a demand node n, a value of $H*x_{hn}$ is added to the x_n value, where x_{hn} is the number of hospitals associated with demand node n and $H \geq 1$ is a user-specified parameter (in Chapter 4, H=500). Fifty-three of the 1,052 demand nodes, are "large users," i.e., single customers using a large quantity of water, such as Universal Studios or the University of Southern California. To more accurately reflect the importance of large users, the x_n values for demand nodes that represent large users are also multiplied by a user-specified factor $L \geq 1$ (in Chapter 4, L=100).

3.13. Conclusions

This chapter describes the discrete event simulation model developed for the post-earthquake restoration of the LADWP water supply system. The input required to run the model and the output it can produce were discussed. Assumptions and modeling issues were presented, including the close interaction with the damage model called GIRAFFE. Preliminary calibration and future application of the model are discussed in Chapters 4 and 5, respectively.

CHAPTER 4

PRELIMINARY CALIBRATION OF THE POST-EARTHQUAKE LADWP WATER SUPPLY SYSTEM RESTORATION MODEL

4.1. Introduction

As a recent, well-documented earthquake affecting the LADWP service area, the 1994 Northridge earthquake offers helpful data for calibrating the post-earthquake restoration model. The initial calibration process and results are discussed in this chapter. First, the actual damage and restoration process are described. The input data used to run the model for the Northridge earthquake are then presented. Finally, the restoration model was run for 10 simulations assuming the Northridge earthquake occurred. The results from those runs were compared to the observed process to determine how well they match and to identify possible future modifications to the model.

4.2. Actual Water Supply System Performance in the Northridge Earthquake

The Northridge earthquake (M_w6.7) occurred at 4:31am PST, January 17, 1994. The epicenter was located in the San Fernando Valley (34°12.53'N, 118°32.44'W) (Figure 4.1). The earthquake caused significant damage to the LADWP water system, mostly concentrated in its northern and central areas. There were 82 repairs made to trunk lines owned by LADWP (70) and MWD (12), and 1,013 repairs made to LADWP distribution pipelines (Jeon and O'Rourke 2005) (Figure 4.1). Lund (1996), Lund et al. (2005), Lund and Davis (2005), and McReynolds and Simmons (1995) provide more detail about the performance of the LADWP water system in the Northridge earthquake.

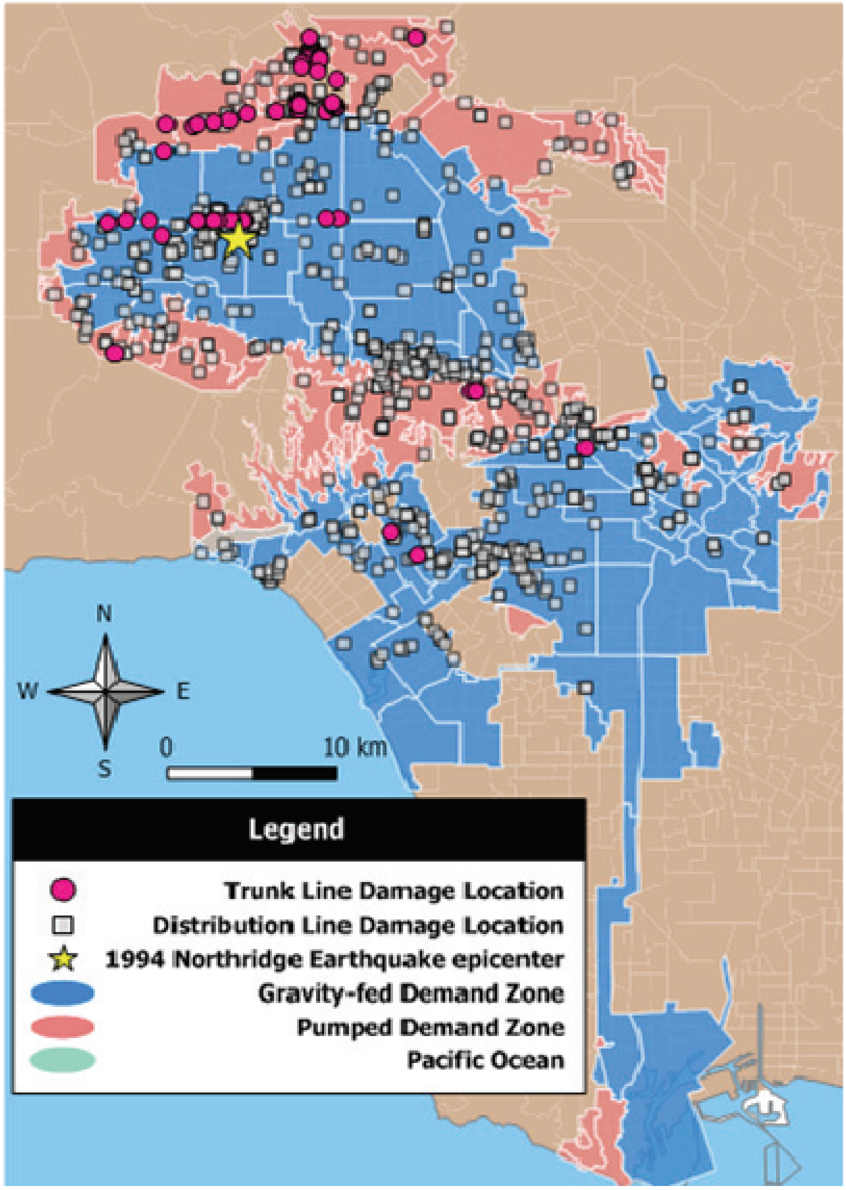


Figure 4.1. Trunk Line and Distribution Line Damage Locations Following the 1994 Northridge Earthquake (Jeon and O'Rourke 2005, Shi 2006)

As a result of the damage, 114,000 service connections (i.e., customers), or roughly 450,000 people, lost water service (Table 4.1). Twenty-five percent of those connections were restored after one day, 65% after 3 days, 94% after 5 days, and virtually all after 7 days (Figure 4.2).

Table 4.1. Actual Number of Service Connections Restored Each Day Following the 1994 Northridge Earthquake, by Pipe Size

Service size (in.)	Jan. 18 1	Jan. 19 2	Jan. 20 3	Jan. 21 4	Jan. 22 5	Jan. 23 6	Jan. 24 7	Total
1	24,989	7,174	35,618	14,259	15,331	3,513	2,353	103,237
1.5	1,508	640	1,130	828	945	171	126	5,348
2	746	373	596	515	632	66	50	2,978
3	94	34	68	91	51	11	9	358
3 equivalent[1]	72	31	35	41	34	-	5	218
4	146	72	83	113	87	4	10	515
6	170	62	79	114	107	6	6	544
8	108	62	58	89	55	2	5	379
10	27	20	10	20	18	2	1	98
12	1	-	-	-	-	-	-	1
Unknown	120	45	58	39	33	2	2	299
Residential[2]	27,529 (24%)	8,297 (7%)	37,505 (33%)	15,773 (14%)	17,026 (15%)	3,763 (3%)	2,545 (2%)	112,438 (100%)
Commercial[2]	452 (29%)	216 (14%)	230 (15%)	336 (22%)	267 (17%)	14 (1%)	22 (1%)	1,537 (100%)
Total	27,981 (25%)	8,513 (7%)	37,735 (33%)	16,109 (14%)	17,293 (15%)	3,777 (3%)	2,567 (2%)	113,975 (100%)
Population[3]	110,116	33,188	150,020	63,092	68,104	15,052	10,180	450,202

[1]Typically refers to two smaller pipes side-by-side that are functionally equivalent to a 3 in. service connection.
[2]Residential is sum of 1 in. to 3 in. and unknown; commercial is sum of 4 in. to 12 in.
[3]Assuming an average of 4 people per service connection, residential only.

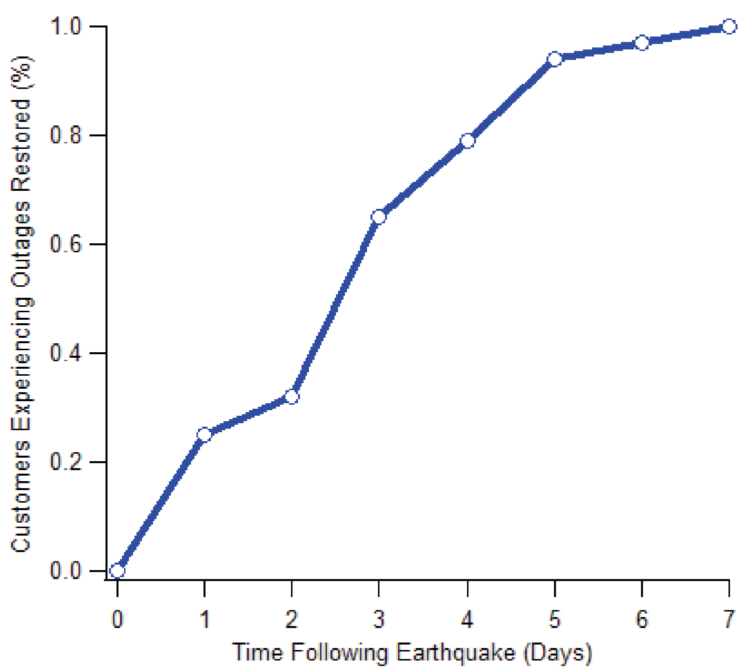


Figure 4.2. System Restoration Curve (percentage of those service connections that lost service restored vs. time)

It is important for the restoration model to match not just the overall system restoration curve, but also the spatial distribution of the restoration, which is shown in Figure 4.3. The areas that had no water service for the longest were the most heavily damaged areas in the northwest San Fernando Valley. Note that the map in Figure 4.3 was drawn by two LADWP employees intimately involved with the post-Northridge restoration process. It is thought to be an accurate overview of the affected outage areas based on the loss and reestablishment of major supply sources and trunk lines. However, the map creators have indicated that the boundaries may not be exact, there may be scattered pockets of outage areas outside the mapped areas, and there may be pockets of outages areas that that extended longer than the zone they are in indicate. These caveats should be kept in mind as the model results are compared to this map.

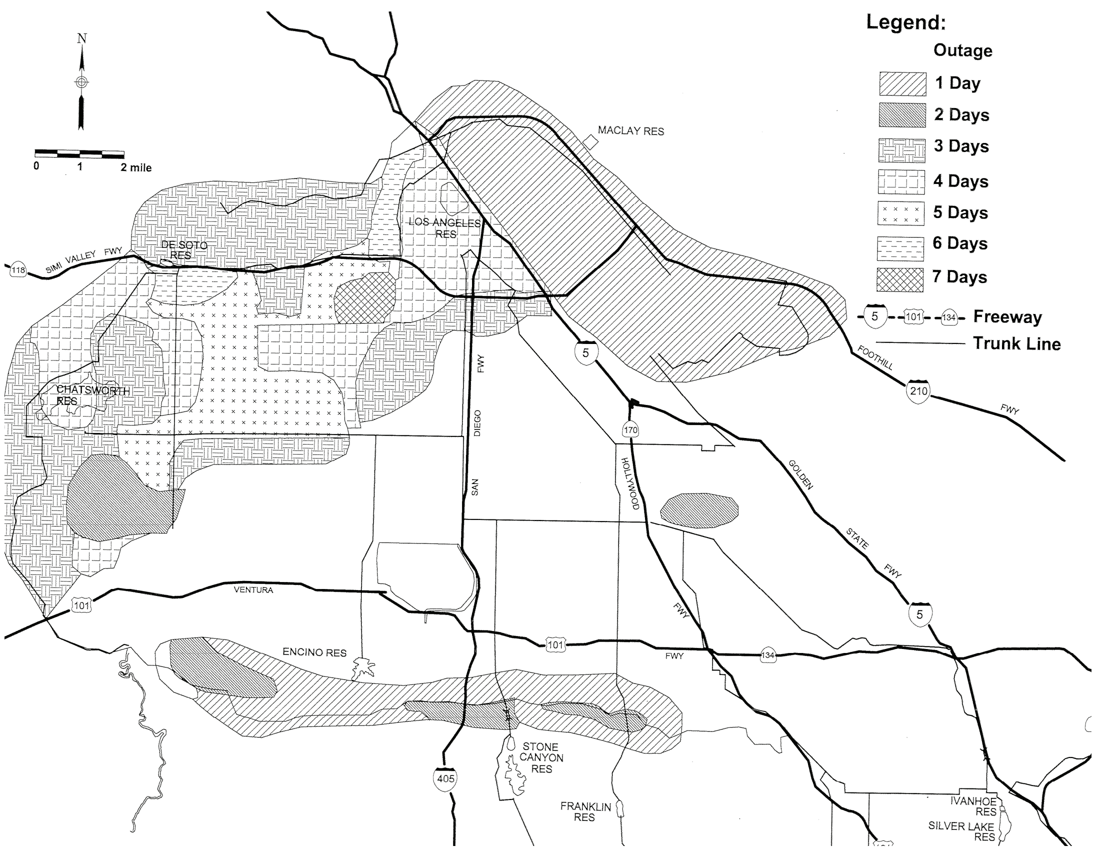


Figure 4.3. Spatial Distribution of the Restoration of Water Outage Areas (Source: Lund et al. 2005)

4.3. Input Data for Model Run with Northridge Scenario

As discussed in Section 3.3, running the restoration model for a specified earthquake scenario requires a description of the initial system damage state in terms of trunk line damage locations and post-earthquake (or normalized) demand for each demand node (to represent distribution pipe damage). Usually, that information is obtained by running GIRAFFE for the specified earthquake scenario. In this case, since the actual damage associated with the earthquake is known, that reported damage was used instead of the GIRAFFE output. GIRAFFE was then run with that initial damage state information to determine the initial serviceability. The trunk line damage information from Jeon and O'Rourke (2005) and Shi (2006) was used directly. Some analysis was required to translate the specific distribution damage locations in Jeon and O'Rourke (2005) into post-earthquake demand at demand nodes, the form required for input into the restoration model.

First, each location of distribution pipeline damage was assigned to the nearest demand node. For each demand node, the total number of damage locations was divided by the length of distribution pipe associated with it to get a repair rate for each demand node.

Second, information from Shi (2006) was used to translate repair rates into normalized demands for each demand node. Shi (2006) used five representative distribution network models to create fragility curves for earthquake demand simulations (Figure 4.4). Each of these network models represents roughly one pressure zone or several small pressure zones within the LADWP water system. The first model or distribution system, 1449, is located in a hillside area in the northeastern part of the LADWP system and has a high mean pressure. Distribution system 1000 is located in a flat area in the southern region of the San Fernando Valley with a moderate mean pressure. Both the 579 and 448 & 462 systems are located in areas that are partly flat and partly hillside, and in northeast Los Angeles central city area. The fifth system, 426, is also located in a flat area, but in the northwest Los Angeles central city area. The mean pressures for the five systems span the range of the whole LADWP water system.

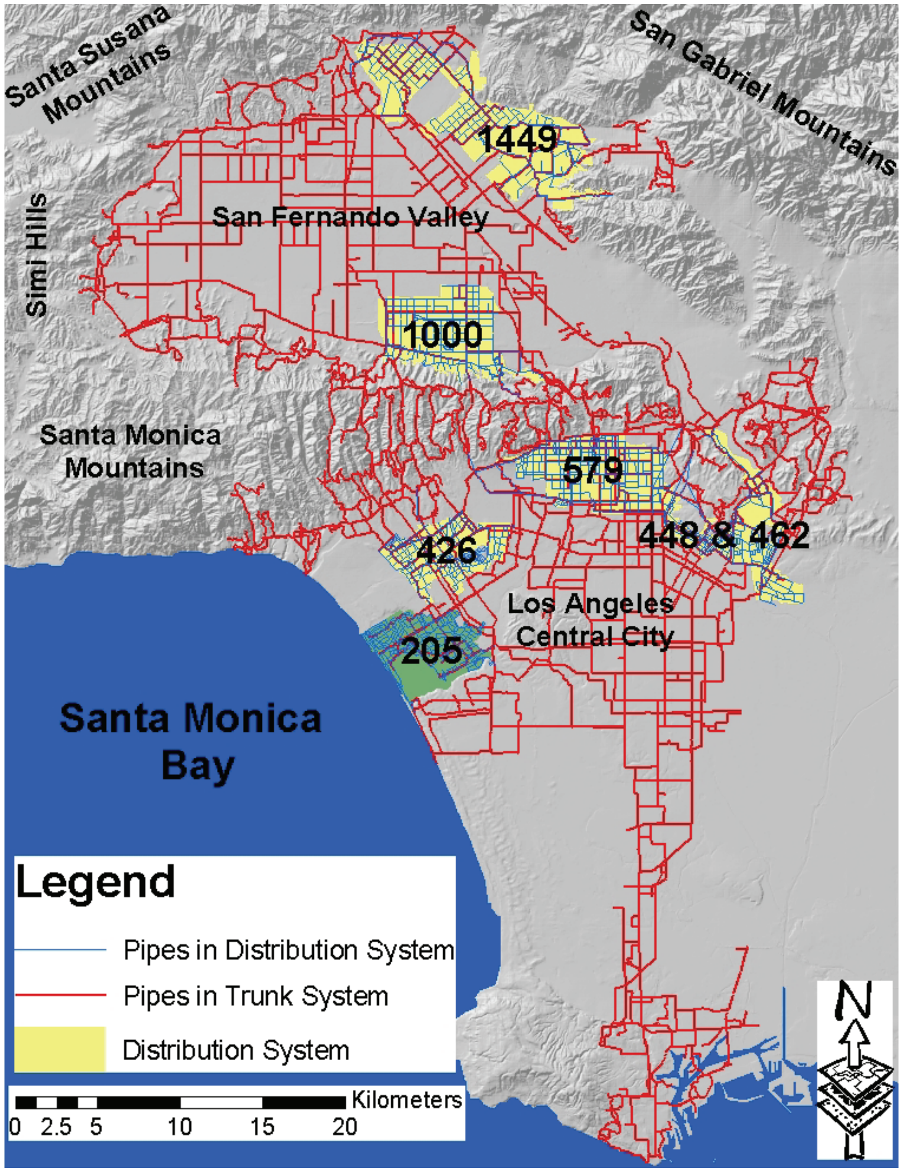


Figure 4.4. Locations of the Six Distribution Systems Used by Shi (2006) to Create Fragility Curves for Earthquake Demand Simulations (Note that the sixth zone, 205, was used to verify the fragility curves of the first five systems.) (Source: Shi 2006)

Shi (2006) used linear regression to formulate a relationship between repair rate, *RR*, and normalized (i.e., pre-earthquake demand/post-earthquake demand) demand:

$$Normalized\ Demand = Mean\ Slope * RR + Mean\ Intercept \tag{4.1}$$

He determined a different *Mean Slope* and *Mean Intercept* for each of the 5 sample distribution systems (Table 4.2). In this calibration study, each Demand Zone was classified as being similar to one of the five sample distribution systems in terms of location and mean pressure (Figure 4.5). The corresponding *Mean Slope* and *Mean Intercept* values were used in Equation 4.1 to translate repair rate into normalized demand for each demand node.

The trunk line damage information from Shi (2006) and Jeon and O'Rourke (2005) and calculated normalized demand values from the process described above were used to create an initial damage state approximately equivalent to the damage from the Northridge earthquake.

As discussed in Section 3.5, the restoration model typically takes in the normalized demand associated with each demand node, and uses that information to estimate the corresponding number of breaks and leaks, which then help determine repair times. In this calibration study, since the actual number of damage locations (breaks plus leaks) associated with each demand node is known, that data was used directly for estimating repair times. It was assumed that 5% of the damage locations were breaks.

Table 4.2. Mean Slope and Mean Intercept Values for the 5 Representative Distribution Systems Used to Find the Normalized Demand from the Repair Rate (Source: Shi 2006)

Distribution System	Mean Slope	Mean Intercept
1449	2.20	1.28
1000	1.82	1.41
579	1.54	1.21
426	1.05	1.15
448 & 462	0.72	1.16

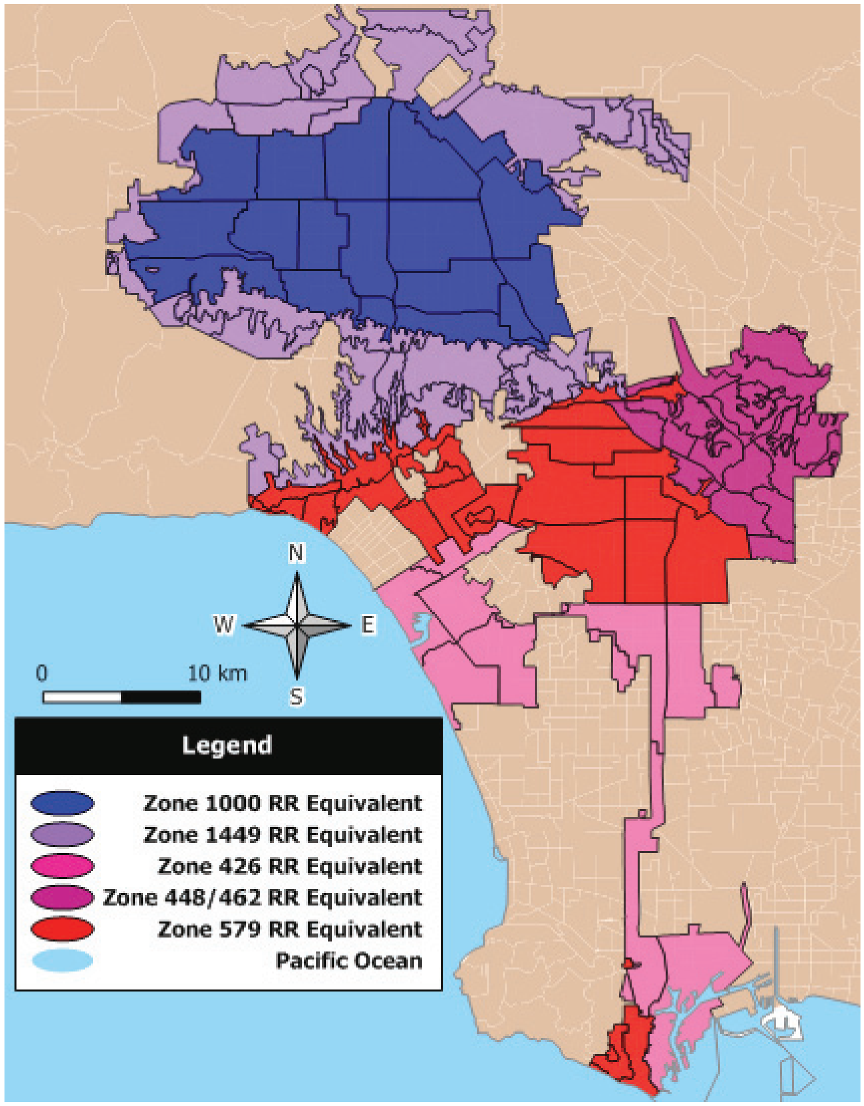


Figure 4.5. Demand Zones Identified as Being Similar to One of the 5 Pressure Zones or Distribution Systems (1000, 1449, 426, 448/462, and 579) Used to Determine Normalized Demand Values for the Demand Nodes (The 5 distribution systems were used by Shi (2006) as representative systems of the 30 distributions making up the LADWP system.)

A few additional assumptions regarding the input damage state should be noted. Of the original 70 trunk line damage locations, 66 are included in this damage state. Shi (2006) did not include detailed damage information for 20 locations on the Granada Trunk Line and 3 locations in the central part of the system, and it was assumed that these locations were breaks. (Based on additional conversations with LADWP personnel, it was recently determined that it would be more appropriate to include only 53 trunk line damage locations in the restoration model run for the Northridge earthquake. The revised recommendation is based partly on new information that has come to light since Shi (2006) and partly on differences between the needs of GIRAFFE and the restoration model. The 53 locations are the ones in which there was damage that affected the hydraulic analysis and that required LADWP crews for restoration work. In the future, the model can be rerun with that revised damage state.) Of the original 1,013 distribution damage locations, 944 were used to determine the normalized demand values in the previous section. The other distribution damages did not have sufficient location and pipeline composition information (Shi 2006).

The method developed by Shi (2006) to determine the normalized demand from the repair rate is only valid for repair rates of 2 repairs/km or smaller. For demand nodes that had repair rates larger than 2 repairs/km, the additional damage was distributed among the node's nearest one or two neighbors to reduce the repair rate to 2.0 or less.

The assumptions made in determining the initial damage state are considered reasonable and should not significantly affect the restoration results. GIRAFFE was calibrated to the Northridge earthquake and shown to match well (Shi 2006). Further, when GIRAFFE was run with this initial damage state, the initial serviceability (percentage of demand met) was 90.3%. The exact serviceability is not known from Northridge, but it is known that approximately 15% of customers experiences water outages.

4.4. Model Results for the Northridge Earthquake

4.4.1. System Restoration Curves

To compare the restoration model results to the Northridge data, 10 simulations were completed. The system restoration curves for all simulations with the actual restoration curve (Figure 4.2) are shown in Figure 4.6. Figure 4.7 shows the variability of restoration curves from the 10 simulations runs with the mean restoration curves and the 90% confidence interval curves plotted. The variability in the model results reflects all the uncertainty included in the restoration model, including uncertainty in task and travel time durations and damage location discovery times. Clearly, in its current form, the restoration model predicts that the restoration occurs too quickly when comparing to the actual Northridge curve, especially in the first day. There are several possible reasons for this, and future work should explore them and modify the model as necessary to achieve a better match.

One possible cause of the mismatch has to do with tanks and reservoirs. Currently the restoration model assumes that tanks and reservoirs will never run out of water. Following the Northridge earthquake, however, some tanks did run dry, resulting in lower system serviceability, additional time required to refill them, and more difficulty finding damage locations in pipes that had run dry. While the restoration model takes into account difficulty in finding damage locations, it does not account for decreased serviceability as a result of dry tanks or reservoirs, or the time required to refill them. A preliminary attempt was made to consider the effect of changing tank and reservoir levels on the restoration process. To do this, the restoration model was adjusted so that the input to GIRAFFE during the restoration simulations considered both the restoration of damage that had taken place during the previous time period, and the quantity of water remaining in the tanks and reservoirs. GIRAFFE can produce as output serviceability at time 0 and at a future user-specified time, such as 12 hours later. The results at the later time are different because they assume that the tank and reservoir levels have been decreasing until that time (Shi 2006). Thus, to determine the system serviceability at time 12 hours, GIRAFFE is run at time 0 hours and results are obtained for time 0 and time 12 hours. The time 0 output information is used to represent the serviceability at time 0 and to make decisions in the restoration model for the first 0 to 12 hours; the time 12 output information is stored as a prediction for the reservoir and tanks' status at time 12 hours. When GIRAFFE is run again at time 12 hours, the input damage state includes the updated pipe damage at time 12 hours and the estimated reservoir and tank levels at time 12 obtained from the previous GIRAFFE run.

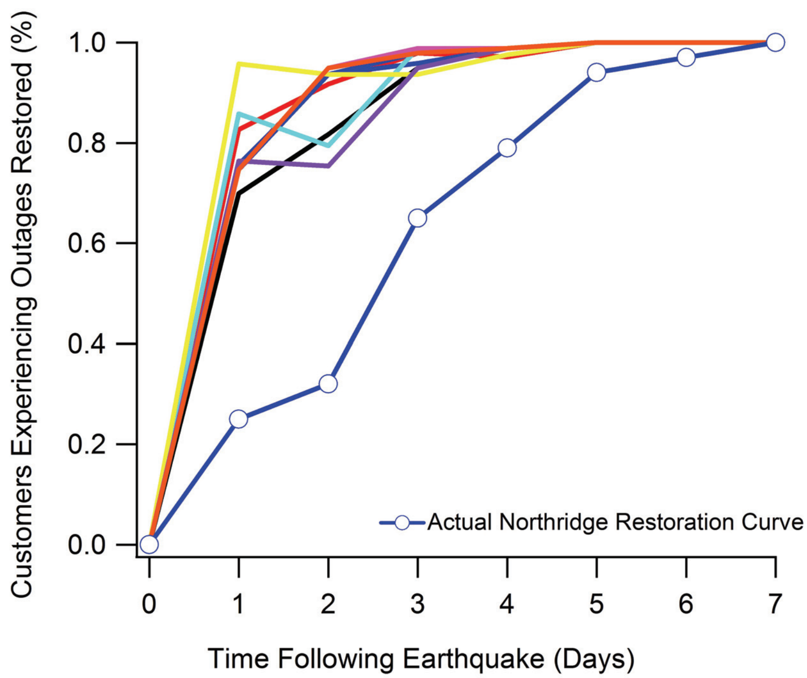


Figure 4.6. Actual Northridge System Restoration Curve (See Figure 4.2) and System Restoration Curves from the Restoration Model Run for 10 Simulations with the Northridge Calibration Damage State Developed in Section 4.3

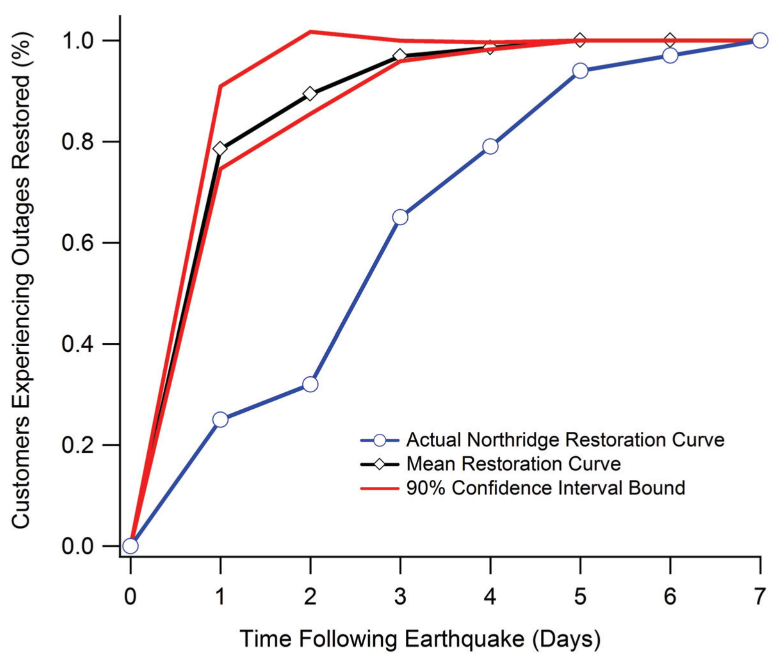


Figure 4.7. Mean System Restoration Curves and 90% Confidence Interval Bounds with the Actual Northridge Restoration Curve (Figure 4.2)

The process is repeated for each 12 or 24 hour time step. Although the reservoir and tank levels at time 12 do not account for pipe restoration that has taken place from 0 to 12 hours, it is considered to be a reasonable estimate of the status at 12 hours.

The restoration model was run for one simulation considering the reservoir and tanks' status as described. In the resulting system restoration curve (Figure 4.8), the serviceability of the system does not reach 1.0, indicating that customers are still without water even after all damage is restored. Following the earthquake, the reservoir and tanks were emptied of too much water and could not serve their customers. Note that whereas in Figures 4.6 and 4.7, the y-axis shows the percentage of those customers who lost service, in Figure 4.8, the y-axis shows restoration as a percentage of all LADWP customers so that one can see that the serviceability declines after time 0. Without refilling the reservoirs and tanks, the system serviceability will never return to 1.0. The original runs that did not consider the decline in reservoir and tank levels and this additional run that considered these level decreases but not refilling, bound the correct solution. The former results in a restoration that is too fast and the latter in a restoration that is too slow. In the future, both the lowering of the reservoir and tanks levels and the process of refilling them should be included in the restoration model.

Other possible reasons that the restoration model currently predicts an overly fast restoration, especially in the first day, are discussed in Section 5.2.1 in the section about possible future model development efforts.

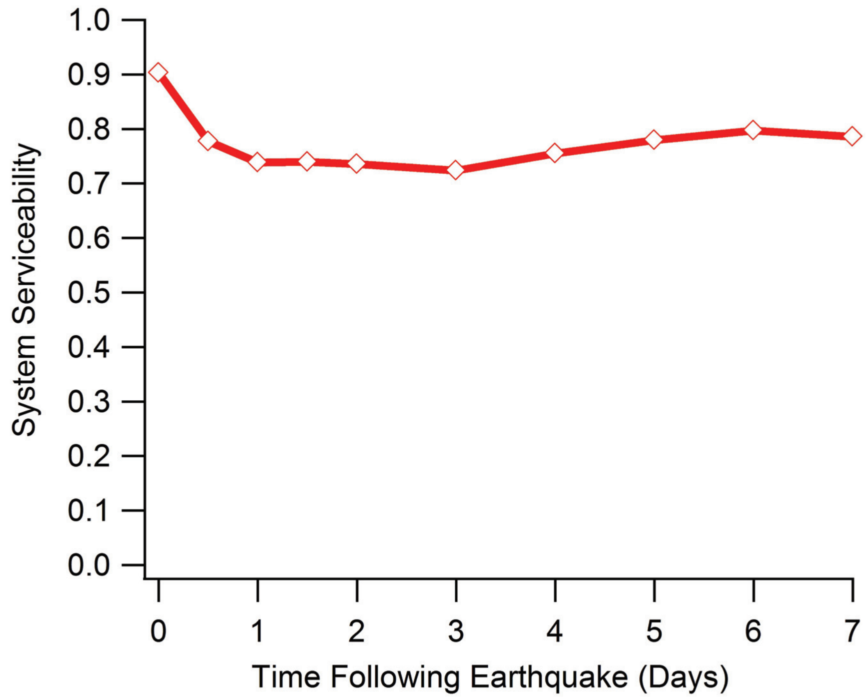


Figure 4.8. System Restoration Curve from Restoration Model Simulation Considering Reservoir and Tank Levels

4.4.2. Spatial Distribution of the Restoration

The spatial distribution of restoration in Northridge was compared to the average time each demand node was restored from the 10 simulations. Figure 4.9 shows the average time each demand node was restored. The longer restore times are located mostly within the northwestern portion of the system. There a few of locations, one in the Santa Monica Mountains south of the San Fernando Valley and in the western Santa Monica Mountains, that required longer restoration times (indicated by red and yellow dots) than what was observed in Northridge (Figure 4.9).

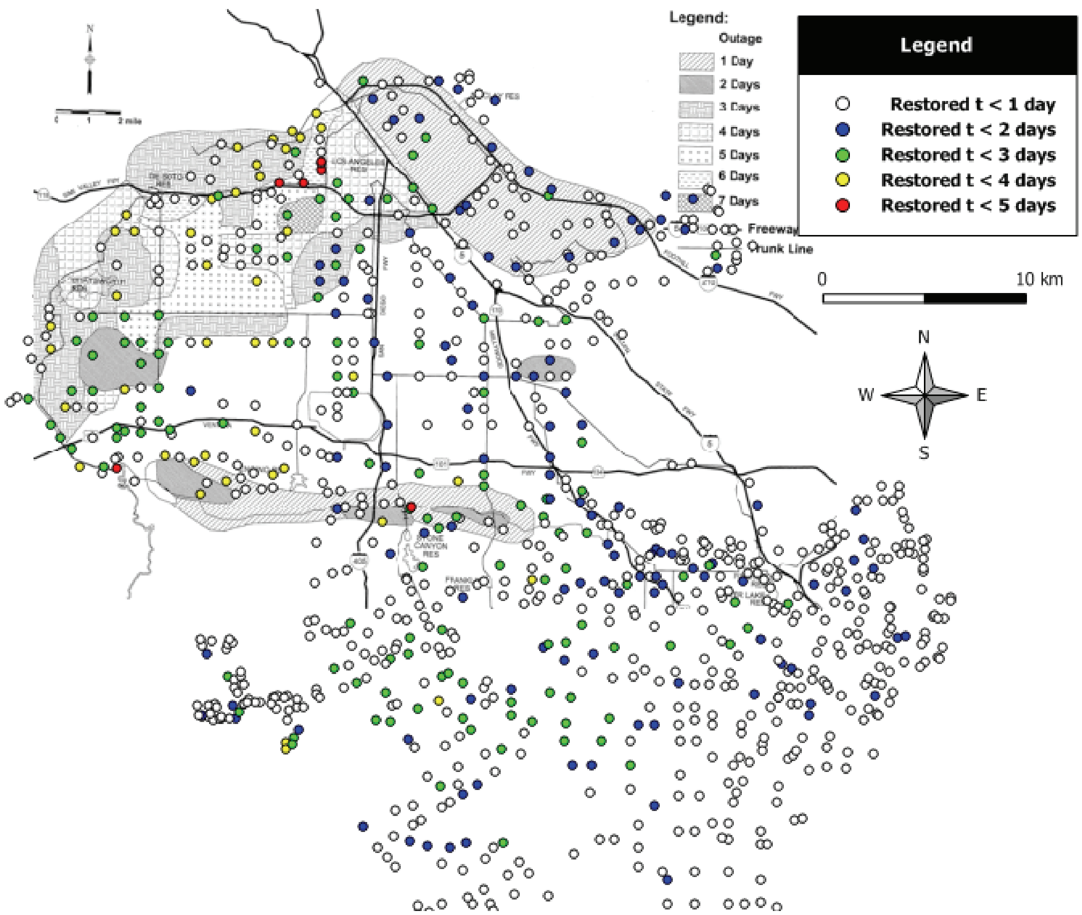


Figure 4.9. Average Time Each Demand Node was Restored in the 10 Simulations Run with the Northridge Calibration Damage State Developed in Section 4.3 with the Outage Map from Figure 4.3

Comparing the results in Figure 4.9 to Figure 4.3, the restoration model was able to simulate longer restoration times in roughly the same locations as they occurred in Northridge. This suggests that future modifications to the model should aim to capture longer restoration times evenly across the system without substantially changing the order in which damage is repaired and service is restored.

4.4.3. Crew and Material Usage

Data on the crews and materials used during the restoration is also available for the 10 simulation runs. The time each crew type from each yard spends working, traveling, and idle is tracked by the restoration model. Results from one of the sample runs discussed in Section 4.4.2 are presented in Table 4.3. One can see, for example, that most of the work was done by crews from the West Valley, Western, and East Valley District Yards, as expected. Repair crews spend more time working than other crews since repair tasks typically take longer than inspection, rerouting, and isolating.

Table 4.3. Summary of Crew Usage Following the Northridge Calibration Earthquake for One Run
(The percentage of total time working, traveling, and idle for each crew type at each yard are assigned.)

(District) Yard Assigned	Type of Crew	Number of Crews	%Time Working	%Time Traveling	%Time Idle
Central District Yard	WD Inspector	20	4.44	0.72	98.84
	WD Repair Crew	34	21.59	1.77	76.64
Western District Yard	WD Inspector	20	11.36	2.62	86.02
	WD Repair Crew	34	48.22	1.84	49.94
East Valley District Yard	WD Inspector	20	9.21	2.22	88.57
	WD Repair Crew	32	41.15	2.40	56.45
Harbor District Yard	WQ&O Inspector	4	0	0	100
	WD Inspector	20	0.06	0.03	99.91
	WD Repair Crew	22	0.39	0.17	99.44
West Valley District Yard	WD Inspector	20	13.45	0.35	86.19
	WD Repair Crew	37	55.48	2.74	41.78
Ripple St. Yard	WQ&O Inspector	16	0	0	100
Tujunga Pump Station Yard	WQ&O Inspector	16	13.45	0.35	86.19

Since the model assumes that crews do not return to their yards between assignments, they do not spend a large percentage of their time traveling. Note that it appears that the crews spend a great deal of time idle largely because many crews work only during one phase. For example, although inspectors may work a lot initially, once inspection is complete, the model considers them to be idle for the remainder of the restoration process.

The amount of each material type used within a district during a 12-hour period is also tracked. Table 4.4 shows the amount of pipeline materials used in the Central, Western, East Valley, and West Valley districts during the same one simulation (no materials were used in Harbor so it is not included). As expected, West Valley, the district with the most damage, used the most repair materials, followed by East Valley and Western. More repair clamps were used that pipe sections and mechanical couplings since pipe leaks were more common than breaks. When using the restoration model in the future, this type of repair material information can be helpful in determining whether sufficient repair materials are available for future earthquakes, and where they should be stored.

4.4.4. Additional Model Results

In addition to the above model outputs, which are likely to be the most useful ones for general application of the model, other output can be generated to provide a more detailed description of how the restoration takes place within a model run. For example, tracking the status of the demand nodes and the trunk lines at the end of each day can show more detail about the order in which tasks are completed. An example of one of the ten simulation runs is shown in Figures 4.10-4.15. The 10 possible status values are listed in Table 3.2. Note that a demand node may still be uninitialized at time 24 hours or later either because there are not enough inspection crews and so it is waiting for a crew to be dispatched to it, or because a damage location has not been discovered yet.

The user can also examine, for example, the rerouting methods and times for each trunk line that is rerouted in the simulation (Figure 4.16 and Table 4.5).

Table 4.4. Number of Distribution Pipeline Materials Used in Each District Every 12 hours for the First 120 Hours from One Simulation of the Northridge Calibration Damage State (Section 4.3)

District Yard	Time Step (hours)	#Mechanical Couplings	#Pipe Sections	#Repair Clamps	#Fire Trucks
Central	12	4	2	28	0
	24	4	2	28	0
	36	0	0	20	0
	48	0	0	8	0
	60	0	0	11	0
	72	0	0	7	0
	84	0	0	0	0
	96	0	0	0	0
	108	0	0	0	0
	120	0	0	0	0
	Total	8	4	102	0
Western	12	16	8	64	0
	24	10	5	73	0
	36	6	3	40	0
	48	2	1	26	0
	60	4	2	44	0
	72	6	3	21	0
	84	4	2	21	0
	96	0	0	0	0
	108	0	0	0	0
	120	0	0	0	0
	Total	48	24	289	0
East Valley	12	2	1	39	0
	24	2	1	50	0
	36	2	1	30	0
	48	2	1	19	0
	60	4	2	42	0
	72	0	0	9	0
	84	0	0	1	0
	96	0	0	0	0
	108	0	0	0	0
	120	0	0	0	0
	Total	12	6	190	0
West Valley	12	0	0	0	0
	24	2	1	39	1
	36	10	5	55	0
	48	6	3	29	0
	60	6	3	52	0
	72	6	3	25	0
	84	6	3	51	0
	96	2	1	19	0
	108	2	1	38	0
	120	0	0	0	0
	Total	40	20	308	1

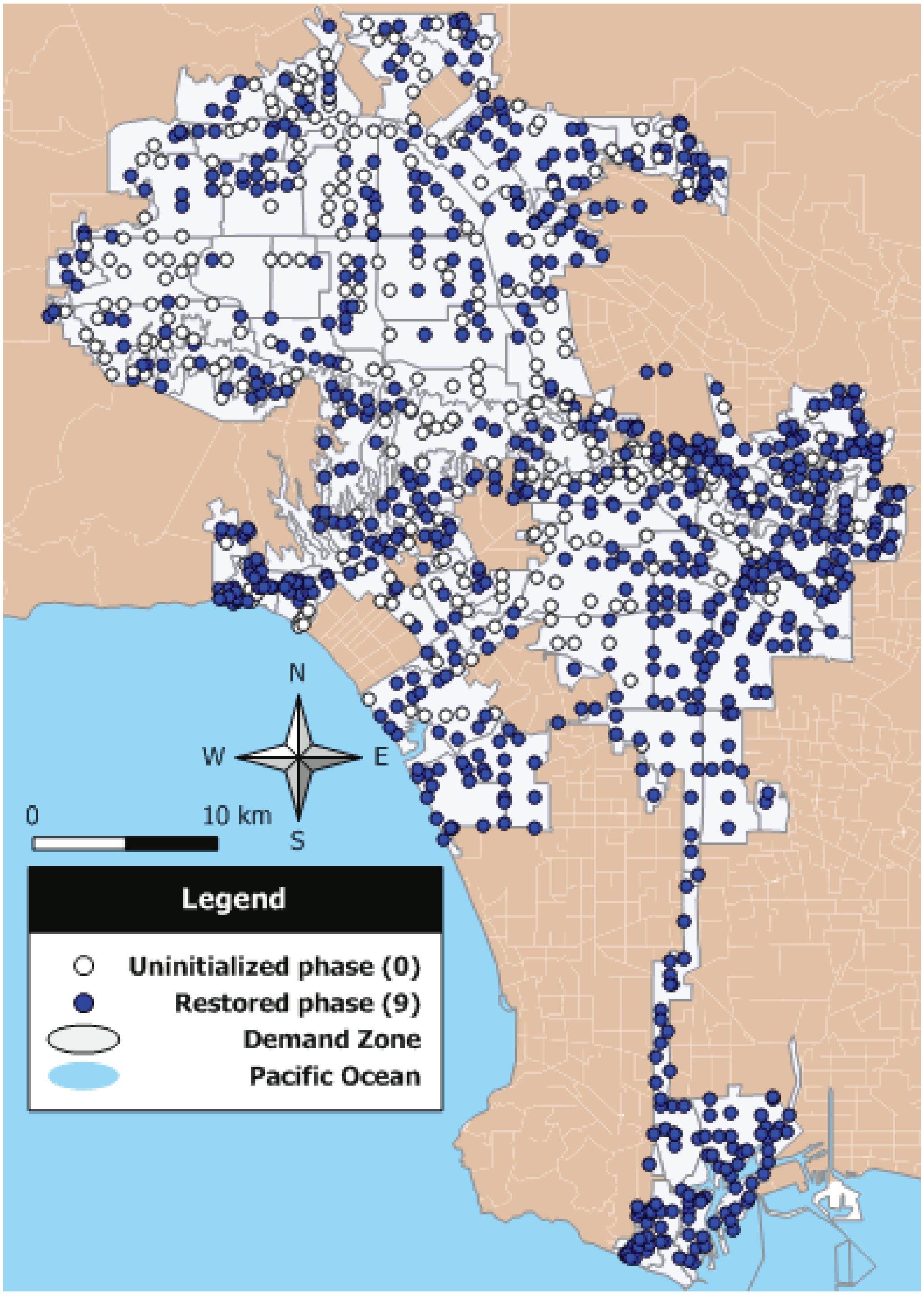


Figure 4.10. Demand Nodes' Status at Time 0 Hours in One Simulation of the Northridge Calibration Damage State (Section 4.3)

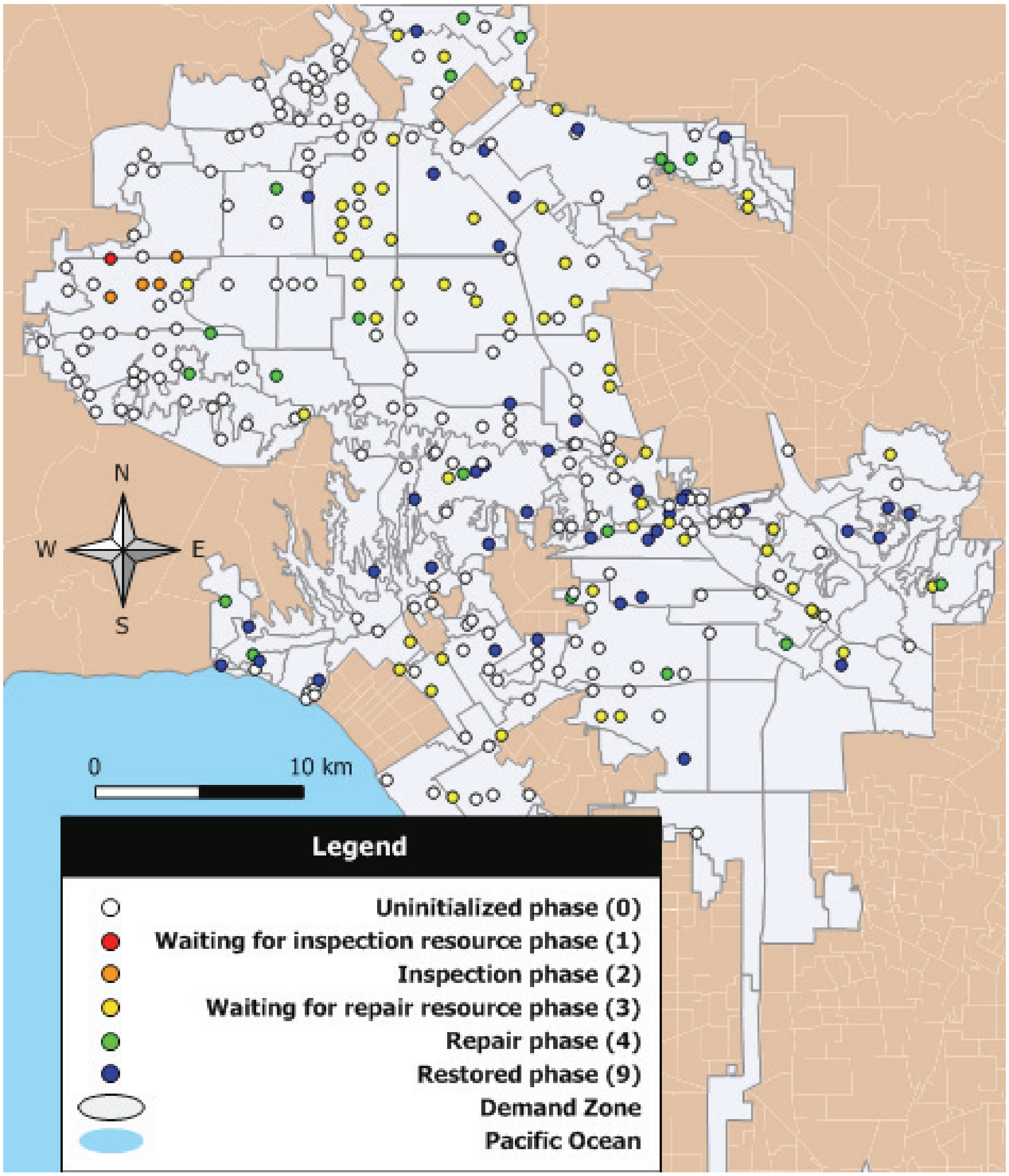


Figure 4.11. Demand Nodes' Status at Time 24 Hours in One Simulation of the Northridge Calibration Damage State (Section 4.3)

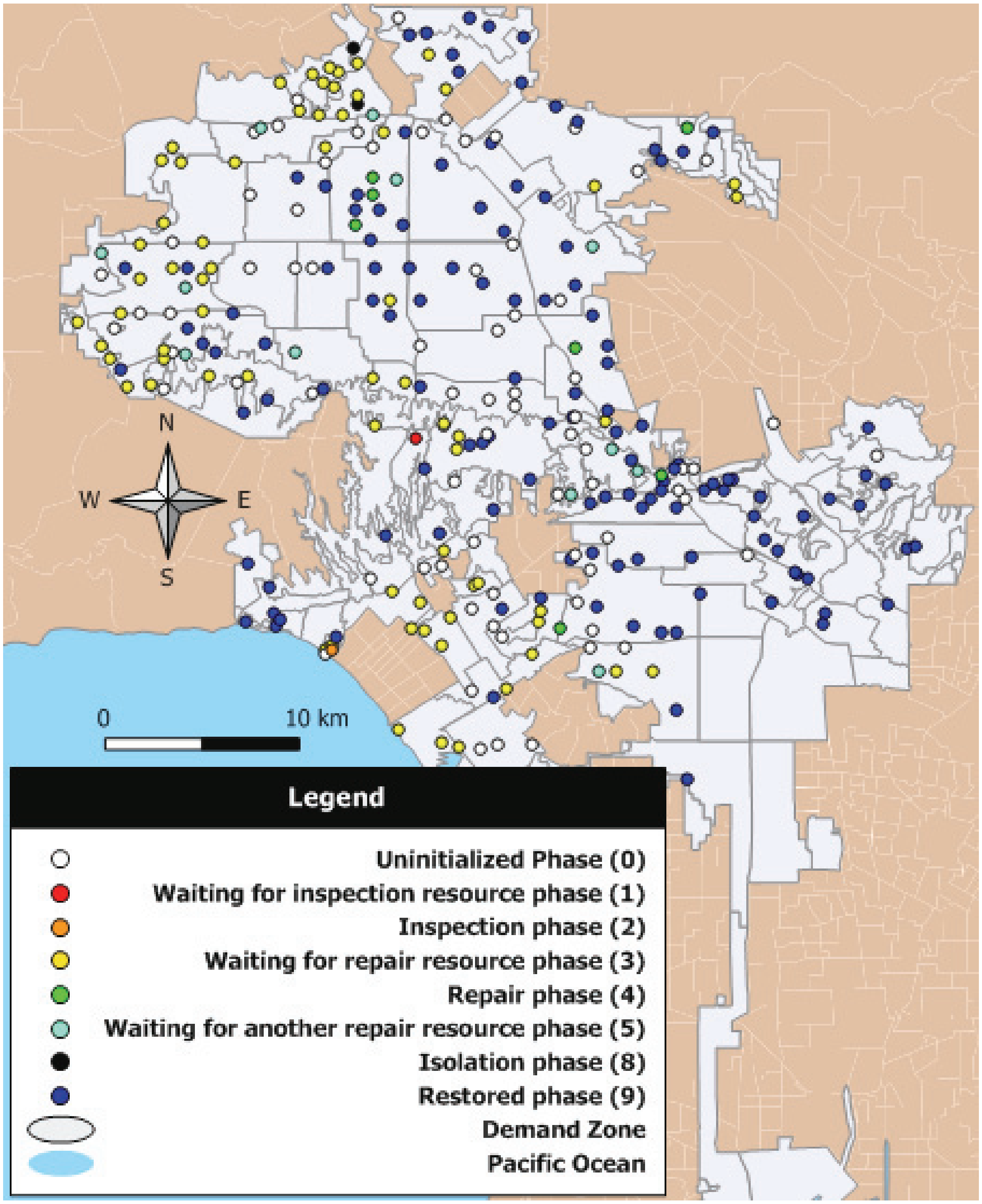


Figure 4.12. Demand Nodes' Status at Time 48 Hours in One Simulation of the Northridge Calibration Damage State (Section 4.3)

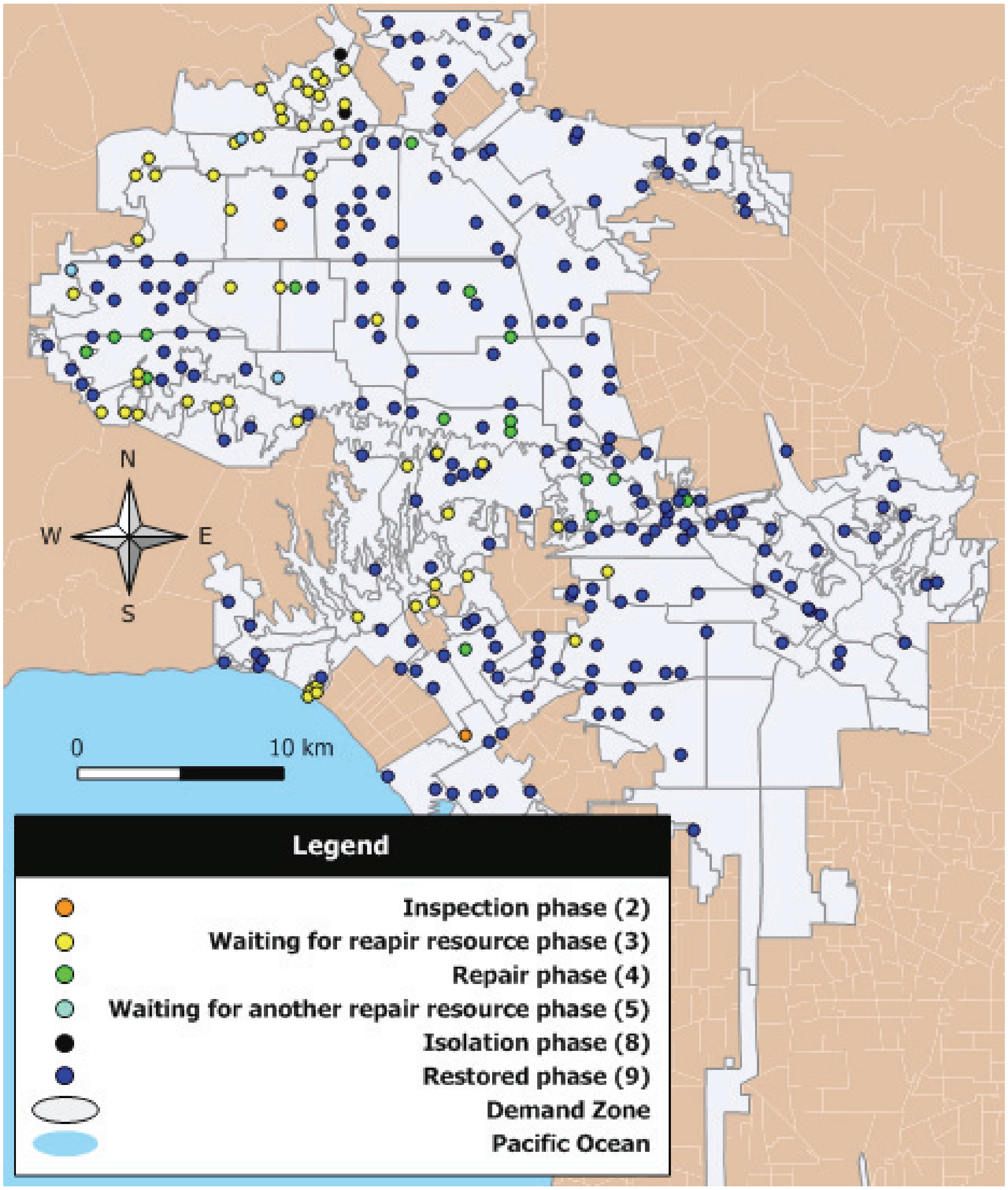


Figure 4.13. Demand Nodes' Status at Time 72 Hours in One Simulation of the Northridge Calibration Damage State (Section 4.3)

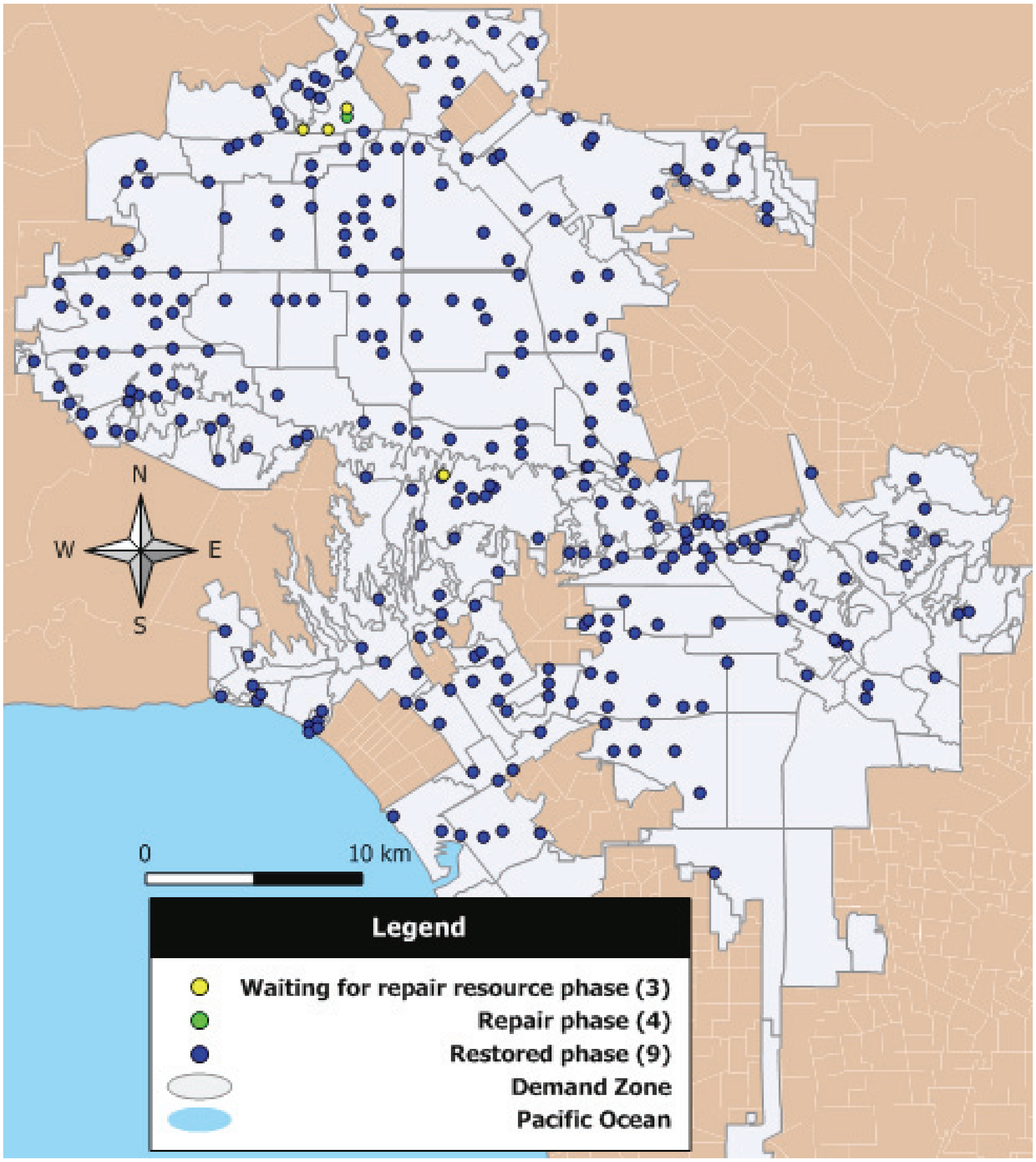


Figure 4.14. Demand Nodes' Status at Time 96 Hours in One Simulation of the Northridge Calibration Damage State (Section 4.3)

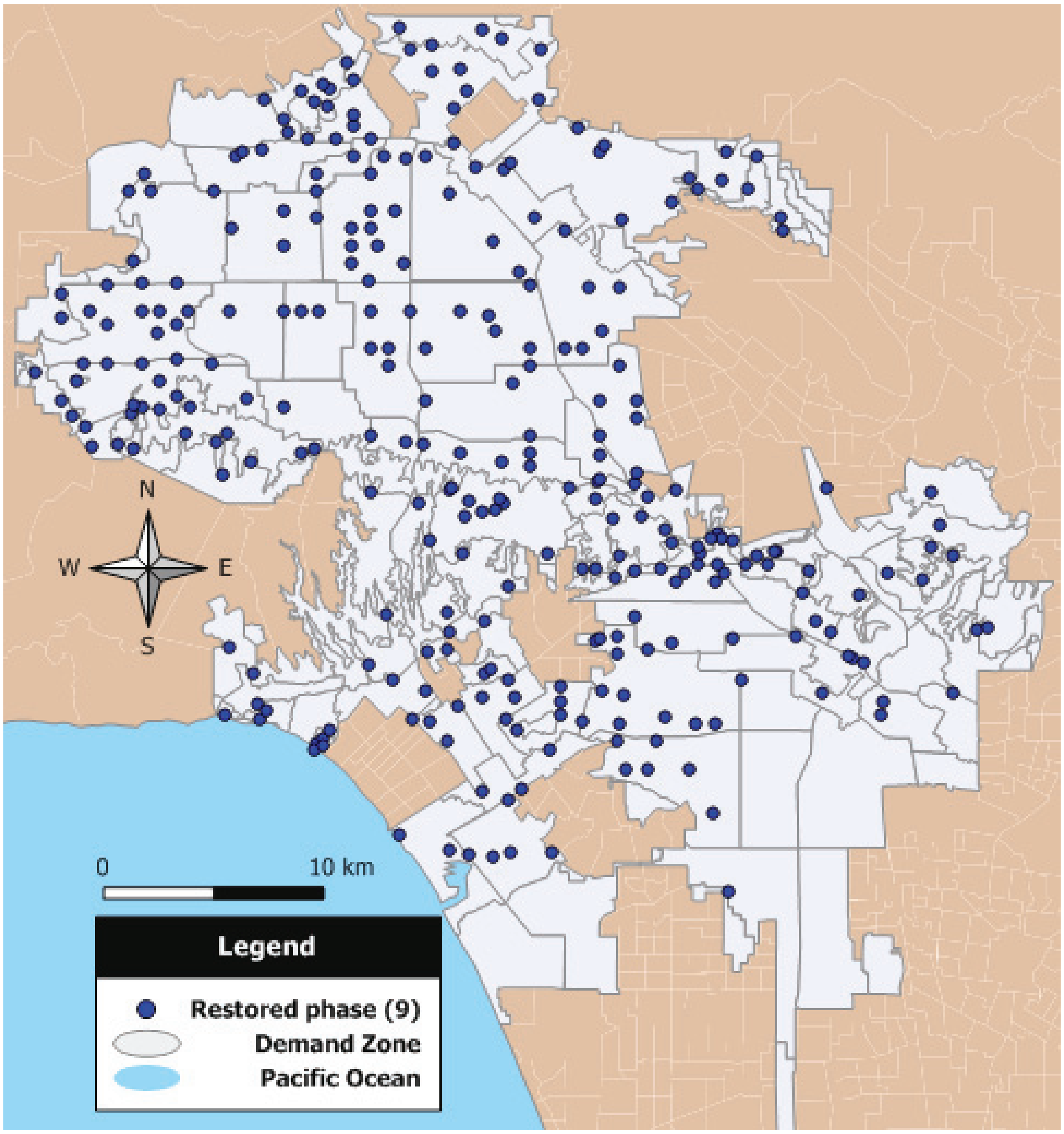


Figure 4.15. Demand Nodes' Status at Time 120 Hours in One Simulation of the Northridge Calibration Damage State (Section 4.3)

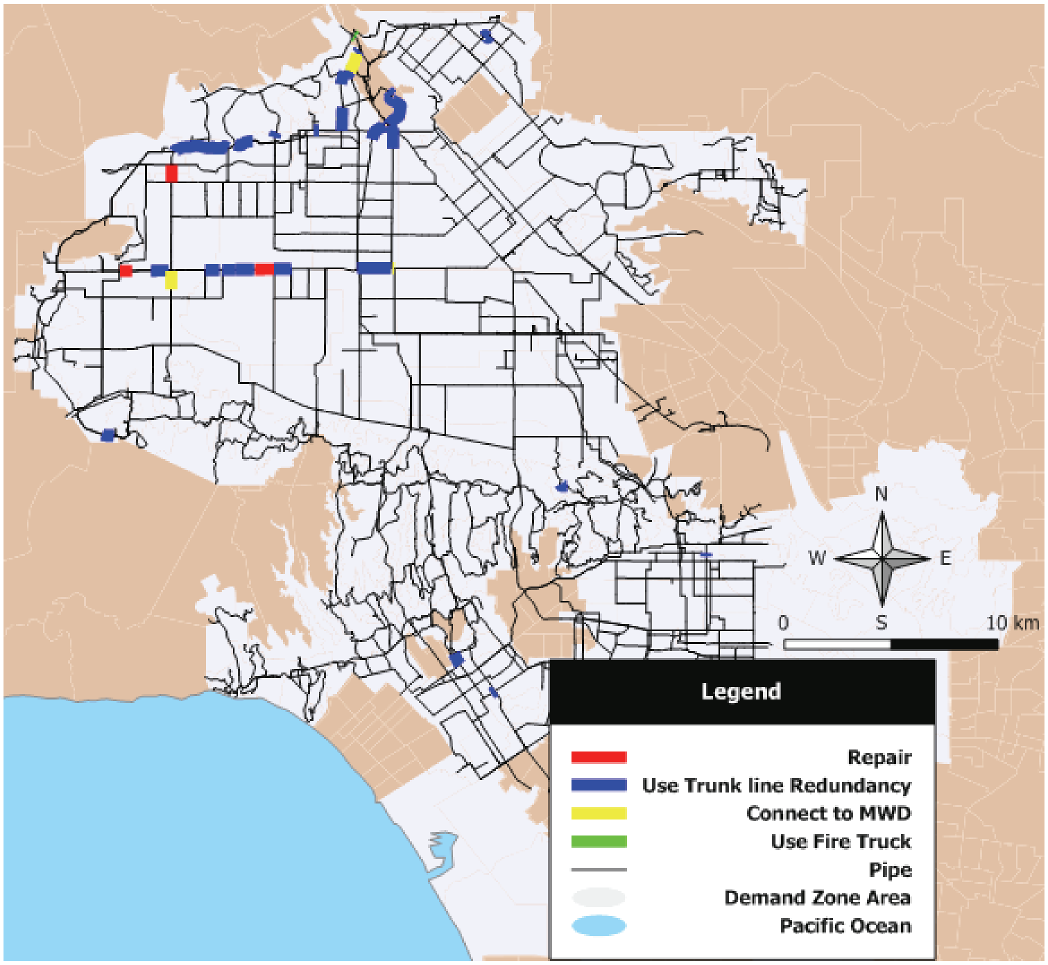


Figure 4.16. Locations of Damaged Trunk Lines from the Northridge Calibration Damage State (Section 4.3) and Rerouting Methods from One Simulation Indicated

Table 4.5. Example Rerouting Methods and Times for Pipes from Simulations of the Northridge Calibration Damage State (Section 4.3)

Pipe ID	Rerouting Method	Total Rerouting Time Duration
GH222	Use Trunk Line Redundancy	21.06 hours
VF1438	Use Trunk Line Redundancy	4.71 hours
GH8382	Connect to MWD	5.85 hours
GH3844	Use Fire Trucks	66.12 hours

Hospital locations are included in the restoration model input, so one could also easily examine the results to see how long hospitals are expected to be without water (Figure 4.17). Since hospitals cannot operate for long without potable water and since they play a critical role in post-earthquake emergency response, this information could be important for emergency response planning.

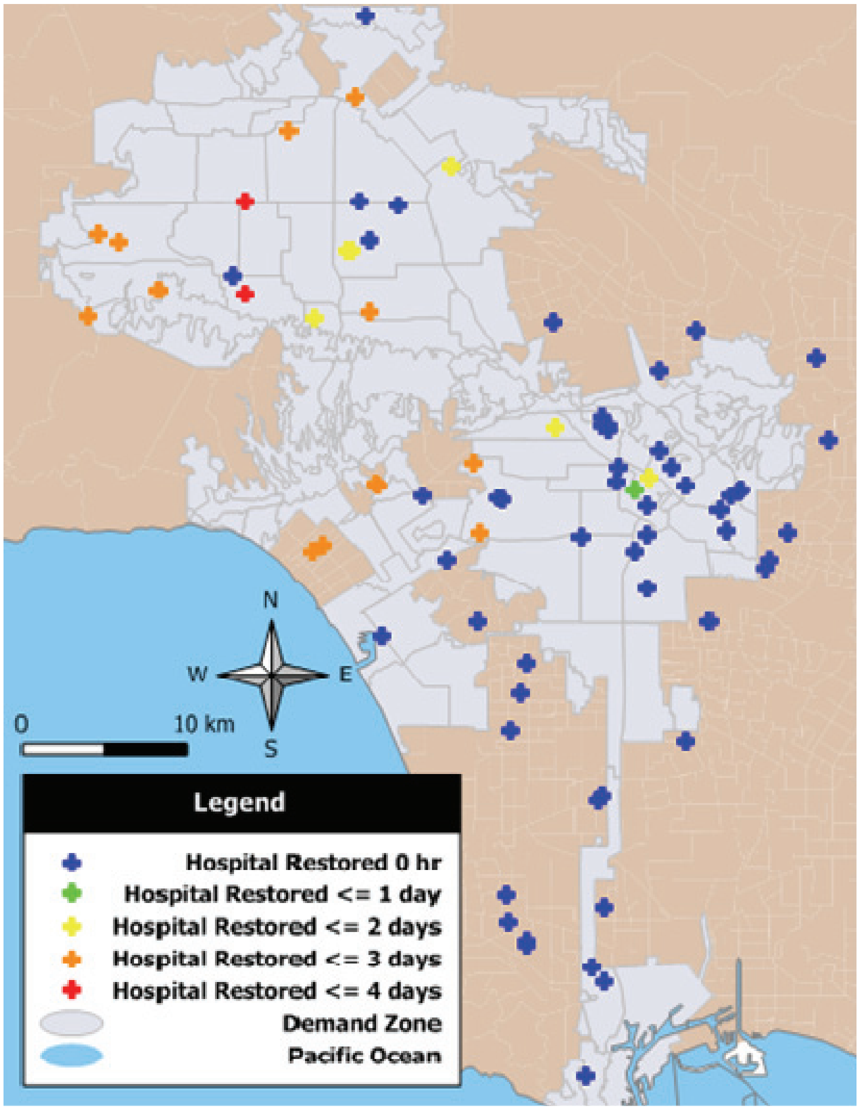


Figure 4.17. Hospital Locations Nearest to the LADWP Service Area and the Estimated Average Time Water is Restored to their Nearest Demand Node from the 10 Simulations of the Northridge Calibration Damage State (Section 4.3)

4.5. Conclusions

In this chapter, the initial calibration of the restoration model using data from the 1994 Northridge earthquake is described. The system restoration curves indicate that the restoration predicted by the restoration model for the Northridge calibration damage state is faster than what was observed in 1994. In terms of the spatial evolution, the restoration model results approximately match the observed restoration. Further work is needed to incorporate the consideration of the reservoir and tank status within the restoration model and to calibrate the model so that the results match the actual data from Northridge more closely.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1. Key Contributions

This report describes the use of discrete event simulation to model the post-earthquake restoration of the Los Angeles water supply system. As mentioned in Chapter 1, this research aims to: (1) advance the state-of-the-art knowledge in post-disaster lifeline restoration modeling, (2) improve post-earthquake loss estimation and resilience assessments, (3) help identify ways to improve post-earthquake restoration and evaluate the relative effectiveness of such strategies, and (4) support post-earthquake fire modeling. The real-life post-earthquake restoration process is described in Chapter 2. In Chapters 3 and 4, respectively, the post-earthquake restoration model for the Los Angeles water supply system and its comparison to the 1994 Northridge earthquake are explained.

Using discrete event simulation for modeling post-earthquake restoration of lifelines is a recent advance, and to the author's knowledge, this report represents the first attempt to apply that technique to water supply system restoration. The resulting restoration model is able to depict the real-life process described in Chapter 2 and the spatial distribution of restoration following the 1994 Northridge earthquake in general (Section 4.3). Although the initial calibration results from the restoration model predicted a faster restoration than what was observed in Northridge, it should be able to match well with modest additional calibration. Compared to previous restoration modeling efforts, this model includes very limited simplifications of the water system and the restoration process, which should lead to a more accurate, highly detailed representation of the restoration process. It interacts closely with the damage and system functionality model for the Los Angeles water system, GIRAFFE, and thus makes use of the most realistic available methods for estimating post-earthquake damage and system functionality. The restoration model produces multiple forms of output, including system and subregion restoration curves with uncertainty estimates, spatial distribution of restoration, and information on crew and material usage. As the first application of discrete event simulation to restoration of water supply systems in particular, the model is novel in representing thousands of entities (compared to tens in electric power) and accommodating a corresponding increase in complexity of the system and the restoration process; coupling the restoration model with a damage and functionality estimation model; and incorporating rerouting and damage isolation explicitly.

When calibrated to the satisfaction of the user, the restoration model can be applied to estimate the restoration for any earthquake. One could apply it for hypothetical future earthquakes for long-term planning, or even immediately following an earthquake to give an early estimate of restoration time before damage assessments are available from the field. Because so many of the utility company's decision variables are represented explicitly in the model, by varying those parameters and seeing their effect on final restoration times, the model can be an aid in evaluating the effectiveness of possible restoration improvement activities. Finally, the model's output may be useful in supporting post-earthquake fire modeling, since water availability is a key determinant of the risk of post-earthquake fire spread.

5.2. Future Work

There is great potential to build on the work presented in this report to further the understanding and improvement of post-earthquake restoration of water supply systems. Avenues for future research can be divided into those related to model development and those related to model application.

5.2.1. Model Development

The restoration model of the Los Angeles water supply system presented in this report has been shown to depict the real-life restoration process in general spatially, but the initial calibration results consistently predicted a faster restoration than what occurred in Northridge.

There is more than can be done to continue its development by calibrating more fully, relaxing some model assumptions, integrating the model with other lifeline restoration models, and improving the programming.

To further improve the accuracy of the restoration model presented here, more calibration of the model should be completed. The model can be modified to achieve a better match between the model results and observations in the Northridge earthquake. It is expected that the modifications required to achieve a satisfactory match will not be major, although it may be necessary to try several different possible adjustments. LADWP personnel can help suggest modifications that might achieve the desired effect and can assess when the match is sufficiently close for practical purposes. Additional calibration can also be performed using other hypothetical earthquakes. For any hypothetical future earthquake, given an initial damage state and the output from the restoration model, LADWP personnel can assess how the results compare with what they expect. This additional calibration can also act as a planning exercise for the LADWP personnel, as they can explore how they would respond to a hypothetical earthquake in the future.

There are some key assumptions adopted in the model that could be relaxed or modified if desired. An important future effort should be to model changes in tank and reservoir levels during the restoration, efforts to refill reservoirs and tanks once they have run dry, and the effect of reopening emergency reservoirs that are currently full of non-potable water, but not connected to the system. Currently the restoration model only considers damage and restoration to the pipelines in the LADWP system. The consideration of other facilities, like tanks, reservoirs, pump stations, and regulator stations, ends with their inspections. Fragility curves for these facilities are now incorporated within GIRAFFE, and later versions of the restoration model can add the rerouting and repair phases to these entities with this available damage information. It is currently assumed that non-major trunk line damage is all rerouted around using trunk line redundancy. This could be changed to include the possibility that some non-major trunk line damage will have to be repaired.

In real life, pipe damage locations that are discovered after the first 12 hours are usually discovered late because the pipes they are in ran dry due to upstream damage before they were found. When the pipes are refilled, the damage is finally located. In the model, currently the time at which each distribution damage location is discovered is sampled randomly without consideration of the status of the pipe until that time (Section 3.9). A future version of the model might be modified so that the damage locations that are discovered late are found in pipes that were dry and are later rewetted, and they are discovered at the time the pipes are rewetted.

The model currently focuses on restoration of non-potable water, assuming water purification notices can accommodate any water quality issues. Although it would likely require significant effort, in the future the restoration model could be extended to consider restoration of potable water as well. That could allow future investigation of possible tradeoffs between restoring water serviced as quickly as possible and ensuring that all water is potable. Other similar modifications are possible, but it is important to keep in mind that the goal is to have the model be as simple as possible, while still producing meaningful and useful results.

Since the restoration model interacts closely with GIRAFFE, any future improvements in GIRAFFE will automatically be included in the restoration model. For example, efforts are currently underway to integrate results from the electric power restoration model developed for LADWP (Çağnan and Davidson, 2007, Çağnan et al. 2006) into GIRAFFE, which should give more accurate predictions of when pump stations that require electric power would be restored. Integrating the restoration model with results from REDARS2, a model of post-earthquake highway system damage and restoration, could increase the accuracy of travel time estimates (Werner et al. 2006).

There are a few programming-related challenges that could also be addressed in future work. The most important effort would be to automate the interaction between the restoration model and GIRAFFE. A more streamlined interaction with GIRAFFE would significantly decrease the time required to run a restoration simulation and provide a more user-friendly restoration model. The restoration model requires a great deal of input data, which takes a lot of pre-processing time to prepare. In the future, the process could also be more automated and streamlined. While the restoration model does not take too long to run at present (one simulation takes approximately 2 hours time on a personal computer with a 1.6 GHz processor and 512 MB of RAM, including the manual interaction with GIRAFFE), with advanced programming knowledge, one could probably reduce the run time further and create a user interface to make the program more user-friendly.

5.2.2. Model Application

A great deal can be learned about post-earthquake water supply restoration by applying the restoration model in different ways. The model can be run numerous times to estimate annual risk for the LADWP system; possible restoration improvement strategies can be evaluated; and a sensitivity analysis of the restoration model could be conducted.

Recently, a suite of 59 earthquake scenarios were developed to describe the seismicity of the LADWP water supply system (Wang 2006). These 59 deterministic earthquake scenarios each have an associated "hazard-consistent" probability of occurrence (Chang et al. 2000) determined so that together, this collection of earthquakes and their occurrence probabilities represent the region's seismicity. The GIRAFFE model has been run to produce 10-15 initial damage states for each of the 59 earthquake scenarios. A number of restoration simulations could be run for each damage state-earthquake combination. By probabilistically combining the results for all damage states and earthquake scenarios, one can estimate the annual probability of exceedence vs. restoration time for the Los Angeles water supply system. Çağnan et al. (2006) describes application of a similar process for the LADWP electric power system.

Once fully calibrated, the model can be a valuable tool for LADWP personnel to explore possible restoration improvement strategies in a risk-free environment. For example, the number of repair crews or the way crews are scheduled can be changed, and by comparing the results with and without the change, one can determine its effect on restoration times and spatial order. The results of exploring different strategies can help LADWP determine the relative effectiveness of different emergency response plans, or the cost effectiveness of changes within their system.

The sensitivity of the restoration model can also be explored in future work. By varying the many parameters included within the model one at a time, one can determine which have the most influence on the final restoration estimates. That understanding can guide future data collection efforts and could help determine if the model can be simplified without negatively impacting the quality of the results it produces.

CHAPTER 6

REFERENCES

Argothy, V. (2003). *Perceptions of Acceptable Levels of Performance of Different Elements in the Built Environment in the Event of a Major Earthquake, Preliminary Paper No. 331*, Disaster Research Center, University of Delaware, Delaware.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and Von Winterfeldt, D. (2003). "A framework to quantitatively assess and enhance the seismic resilience of communities." *Earthquake Spectra,* 19, 733-752.

Çağnan, Z. (2005). *Post-earthquake Restoration Modeling for Critical Lifeline Systems*, Ph.D. Dissertation, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York

Çağnan, Z. and Davidson, R. (2007). "Discrete event simulation of the post earthquake restoration process for electric power systems." *International Journal of Risk Assessment and Management*, 7(8), 1138-1156.

Cağnan, Z. and Davidson, R. (2003). "Post-earthquake lifeline service restoration modeling." *Proc., Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering*, Long Beach, Ca., 255-264.

Çağnan, Z., Davidson, R., and Guikema, S. (2006). "Post-earthquake restoration planning for Los Angeles electric power." *Earthquake Spectra*, 22(3), 1-20.

Chang, S. E., Shinozuka, M. and Moore, J. (2000). "Probabilistic earthquake scenarios: Extending risk analysis methodologies to spatially distributed systems." *Earthquake Spectra*, 16, 557-572.

Dahlhamer, J. M. and Tierney, K. J. (1997). "Winners and losers: Predicting business disaster recovery outcomes following the Northridge earthquake." *Proc., Annual meeting of the American Sociological Association*, Toronto, Ontario, Canada, 9-13.

Eguchi, R. T. and Chung, R. M. (1995). "Performance of lifelines during the January 17, 1994 Northridge earthquake." *Proc., Fourth U.S. Conference on Lifeline Earthquake Engineering: Technical Council on Lifeline Earthquake Engineering*, ASCE, San Francisco, Ca., 120-127.

Jeon, S.-S. and O'Rourke, T. D. (2005). "Northridge earthquake effects on pipelines and residential buildings." *Bulletin of the Seismological Society of America*, 95(1), 294-318.

Law, A., and Kelton, W. D. (2000). *Simulation Modeling and Analysis*, 3rd Ed. McGraw-Hill Inc, New York.

Liu, H. (2006). *Statistical modeling of electric power outage counts and restoration times during hurricanes and ice storms*, Ph.D. dissertation, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York.

Liu, H., Davidson, R., and Apanasovich, T. (2007) "Statistical forecasting of electric power restoration times in hurricanes and ice storms." *IEEE Transactions on Power Systems*, 22(4), 2270-2279.

Los Angeles Department of Water and Power Water Distribution Business Unit (LADWP WD). *Emergency Response Plan*.

Los Angeles Department of Water and Power Water Engineering and Technical Services Business Unit (LADWP WETS). (2001). *Emergency Response Plan*.

Los Angeles Department of Water and Power Water Quality and Operations Business Unit (LADWP WQ&O). (2005). *Emergency Response Plan*, Los Angeles, Ca.

Los Angeles Department of Water and Power (LADWP). (2007). <http://www.ladwp.com> (Mar. 16, 2007).

Lund, L. (1996). "Lifeline utilities performance in the 17 January 1994 Northridge, California earthquake." *Bulletin of the Seismological Society of America*, 86(1B), S350-S361.

Lund, L. and Davis, C. (2005). "Multihazard mitigation Los Angeles water system: A historical perspective." *Infrastructure Risk Management Processes: Natural, Accidental, and Deliberate Hazards*, 224-279.

Lund, L., Davis, C. A., and Adams, M. L. (2005). "Water system seismic performance 1994 Northridge-1995 Kobe earthquakes." *Proc., Fourth Japan-US Workshop on Seismic Measures for Water Supply*, AWWARF/FWWA, Kobe, Japan.

McReynolds, L., and Simmons, R. L. (1995). "LA's rehearsal for the big one." *Journal of the American Water Works Association*, 87(5), 65-70.

Newsom, D. (1977). *Evaluating lifeline response to earthquakes: A simulation methodology*, Ph.D. dissertation, Purdue University., West Lafayette, Indiana.

Ross, M. S. (2002). *Simulation*. Academic Press, San Diego, California

Rossman, L. A. (2000). *EPANET 2 Users Manual*. National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Shi, P. (2006). *Seismic Response Modeling of Water Supply Systems*, Ph.D. Dissertation, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York.

Tierney, K. J. (2000). *Public Support and Priorities for Seismic Rehabilitation in the East Bay Region of Northern California*, Preliminary Paper No. 296. Disaster Research Center, University of Delaware, Delaware.

Tierney, K. J. (1997). "Business impacts of the Northridge earthquake." *Journal of Contingencies and Crisis Management*, 5(2), 87-97.

Tierney, K. J. and Dahlhamer, J. M. (1998). "Earthquake vulnerability and emergency preparedness among businesses." *Engineering and Socioeconomic Impacts of Earthquakes: An Analysis of Electricity Lifeline Disruptions in the New Madrid Area*, Multidisciplinary Center for Earthquake Engineering Research, Buffalo New York, 53-74.

Wang, Y. (2006). *Seismic Performance Evaluation of Water Supply Systems*, Ph.D. Dissertation, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York.

Werner, S., Taylor, C., Cho, S., Lavoie, J.-P., Huyck, C., Eitzel, C., Chung, H., and Eguchi, R. (2006). *REDARS2 Methodology and Software for Seismic Risk Analysis of Highway Systems, Technical Manual*, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, New York.

Xu, M., Guikema, S., Davidson, R., Nozick, L., Cağnan, Z., and Vaziri, K. (2007). "Optimizing scheduling of post-earthquake electric power restoration tasks." *Special Issue: Electric Power, Earthquake Engineering and Structural Dynamics*, 36(2), 265-284.

APPENDIX A

REROUTING METHOD TIMES FOR MAJOR LADWP TRUNK LINES

Table A.1. Rerouting Methods Available for the Major Trunk Lines in the LADWP System, with Estimates of the Time Required to Complete the Rerouting Operation for One Damage Location

Trunk Line Name	Rerouting Method[1]	Minimum Time	Most Likely Time	Maximum Time
Foothill	Use trunk line redundancy	4 hours	6 hours	12 hours
	Use fire trucks	1 day	2 days	3 days
L.A. City	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
	Connect to groundwater well	6 hours	8 hours	12 hours
Haskell	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
Hayvenhurst	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
East L.A.	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
	Use fire trucks	1 day	2 days	3 days
Ivanhoe Outlet	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
	Connect to groundwater well	4 hours	6 hours	8 hours
Silverlake Outlet	Use trunk line redundancy	3 hours	4 hours	8 hours
Harbor	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
	Connect to groundwater well	6 hours	8 hours	12 hours
Van Ness	Use trunk line redundancy	3 hours	4 hours	8 hours

[1]For each trunk line, only those methods listed are possible.

Table A.1. (Continued)

Trunk Line Name	Rerouting Method[1]	Minimum Time	Most Likely Time	Maximum Time
Cahuenga	Use trunk line redundancy	3 hours	4 hours	8 hours
Franklin-Baldwin	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
Venice-Franklin	Use trunk line redundancy	3 hours	4 hours	8 hours
Lower Stone Canyon Outlet	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
Westgate	None			
Upper Stone Canyon Reservoir Outlet	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
Eagle Rock-Hollywood Conduit	Use trunk line redundancy	3 hours	4 hours	8 hours
Hollywood Inlet	Use trunk line redundancy	4 hours	6 hours	8 hours
	Connect to groundwater well	6 hours	8 hours	12 hours
River Supply Conduit	Use trunk line redundancy	6 hours	8 hours	12 hours
	Connect to groundwater well	4 hours	6 hours	12 hours
Stone Canyon Inlet	Use trunk line redundancy	3 hours	4 hours	8 hours
	Connect to MWD	4 hours	6 hours	8 hours
Encino Inlet	Use trunk line redundancy	3 hours	4 hours	8 hours
Susana	Use fire trucks	1 day	2 days	3 days
Granada	Use trunk line redundancy	6 hours	12 hours	1 day
	Connect to MWD	3 hours	6 hours	12 hours
	Use fire trucks	2 days	3 days	4 days
De Soto	Connect to MWD	3 hours	6 hours	12 hours
Roscoe	Use trunk line redundancy	3 hours	6 hours	12 hours

[1]For each trunk line, only those methods listed are possible.

MCEER Technical Reports

MCEER publishes technical reports on a variety of subjects written by authors funded through MCEER. These reports are available from both MCEER Publications and the National Technical Information Service (NTIS). Requests for reports should be directed to MCEER Publications, MCEER, University at Buffalo, State University of New York, Red Jacket Quadrangle, Buffalo, New York 14261. Reports can also be requested through NTIS, 5285 Port Royal Road, Springfield, Virginia 22161. NTIS accession numbers are shown in parenthesis, if available.

NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275, A04, MF-A01).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341, A04, MF-A01).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0005 "A Finite Element Formulation for Nonlinear Viscoplastic Material Using a Q Model," by O. Gyebi and G. Dasgupta, 11/2/87, (PB88-213764, A08, MF-A01).

NCEER-87-0006 "Symbolic Manipulation Program (SMP) - Algebraic Codes for Two and Three Dimensional Finite Element Formulations," by X. Lee and G. Dasgupta, 11/9/87, (PB88-218522, A05, MF-A01).

NCEER-87-0007 "Instantaneous Optimal Control Laws for Tall Buildings Under Seismic Excitations," by J.N. Yang, A. Akbarpour and P. Ghaemmaghami, 6/10/87, (PB88-134333, A06, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0008 "IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame - Shear-Wall Structures," by Y.J. Park, A.M. Reinhorn and S.K. Kunnath, 7/20/87, (PB88-134325, A09, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0009 "Liquefaction Potential for New York State: A Preliminary Report on Sites in Manhattan and Buffalo," by M. Budhu, V. Vijayakumar, R.F. Giese and L. Baumgras, 8/31/87, (PB88-163704, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0010 "Vertical and Torsional Vibration of Foundations in Inhomogeneous Media," by A.S. Veletsos and K.W. Dotson, 6/1/87, (PB88-134291, A03, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0011 "Seismic Probabilistic Risk Assessment and Seismic Margins Studies for Nuclear Power Plants," by Howard H.M. Hwang, 6/15/87, (PB88-134267, A03, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0012 "Parametric Studies of Frequency Response of Secondary Systems Under Ground-Acceleration Excitations," by Y. Yong and Y.K. Lin, 6/10/87, (PB88-134309, A03, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0013 "Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317, A05, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0014 "Modelling Earthquake Ground Motions in Seismically Active Regions Using Parametric Time Series Methods," by G.W. Ellis and A.S. Cakmak, 8/25/87, (PB88-134283, A08, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0015 "Detection and Assessment of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 8/25/87, (PB88-163712, A05, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0016 "Pipeline Experiment at Parkfield, California," by J. Isenberg and E. Richardson, 9/15/87, (PB88-163720, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0017 "Digital Simulation of Seismic Ground Motion," by M. Shinozuka, G. Deodatis and T. Harada, 8/31/87, (PB88-155197, A04, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0018 "Practical Considerations for Structural Control: System Uncertainty, System Time Delay and Truncation of Small Control Forces," J.N. Yang and A. Akbarpour, 8/10/87, (PB88-163738, A08, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0019 "Modal Analysis of Nonclassically Damped Structural Systems Using Canonical Transformation," by J.N. Yang, S. Sarkani and F.X. Long, 9/27/87, (PB88-187851, A04, MF-A01).

NCEER-87-0020 "A Nonstationary Solution in Random Vibration Theory," by J.R. Red-Horse and P.D. Spanos, 11/3/87, (PB88-163746, A03, MF-A01).

NCEER-87-0021 "Horizontal Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by A.S. Veletsos and K.W. Dotson, 10/15/87, (PB88-150859, A04, MF-A01).

NCEER-87-0022 "Seismic Damage Assessment of Reinforced Concrete Members," by Y.S. Chung, C. Meyer and M. Shinozuka, 10/9/87, (PB88-150867, A05, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0023 "Active Structural Control in Civil Engineering," by T.T. Soong, 11/11/87, (PB88-187778, A03, MF-A01).

NCEER-87-0024 "Vertical and Torsional Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by K.W. Dotson and A.S. Veletsos, 12/87, (PB88-187786, A03, MF-A01).

NCEER-87-0025 "Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America," October 20-22, 1987, edited by K.H. Jacob, 12/87, (PB88-188115, A23, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0026 "Report on the Whittier-Narrows, California, Earthquake of October 1, 1987," by J. Pantelic and A. Reinhorn, 11/87, (PB88-187752, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0027 "Design of a Modular Program for Transient Nonlinear Analysis of Large 3-D Building Structures," by S. Srivastav and J.F. Abel, 12/30/87, (PB88-187950, A05, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0028 "Second-Year Program in Research, Education and Technology Transfer," 3/8/88, (PB88-219480, A04, MF-A01).

NCEER-88-0001 "Workshop on Seismic Computer Analysis and Design of Buildings With Interactive Graphics," by W. McGuire, J.F. Abel and C.H. Conley, 1/18/88, (PB88-187760, A03, MF-A01). This report is only available through NTIS (see address given above).

NCEER-88-0002 "Optimal Control of Nonlinear Flexible Structures," by J.N. Yang, F.X. Long and D. Wong, 1/22/88, (PB88-213772, A06, MF-A01).

NCEER-88-0003 "Substructuring Techniques in the Time Domain for Primary-Secondary Structural Systems," by G.D. Manolis and G. Juhn, 2/10/88, (PB88-213780, A04, MF-A01).

NCEER-88-0004 "Iterative Seismic Analysis of Primary-Secondary Systems," by A. Singhal, L.D. Lutes and P.D. Spanos, 2/23/88, (PB88-213798, A04, MF-A01).

NCEER-88-0005 "Stochastic Finite Element Expansion for Random Media," by P.D. Spanos and R. Ghanem, 3/14/88, (PB88-213806, A03, MF-A01).

NCEER-88-0006 "Combining Structural Optimization and Structural Control," by F.Y. Cheng and C.P. Pantelides, 1/10/88, (PB88-213814, A05, MF-A01).

NCEER-88-0007 "Seismic Performance Assessment of Code-Designed Structures," by H.H-M. Hwang, J-W. Jaw and H-J. Shau, 3/20/88, (PB88-219423, A04, MF-A01). This report is only available through NTIS (see address given above).

NCEER-88-0008 "Reliability Analysis of Code-Designed Structures Under Natural Hazards," by H.H-M. Hwang, H. Ushiba and M. Shinozuka, 2/29/88, (PB88-229471, A07, MF-A01). This report is only available through NTIS (see address given above).

NCEER-88-0009 "Seismic Fragility Analysis of Shear Wall Structures," by J-W Jaw and H.H-M. Hwang, 4/30/88, (PB89-102867, A04, MF-A01).

NCEER-88-0010 "Base Isolation of a Multi-Story Building Under a Harmonic Ground Motion - A Comparison of Performances of Various Systems," by F-G Fan, G. Ahmadi and I.G. Tadjbakhsh, 5/18/88, (PB89-122238, A06, MF-A01). This report is only available through NTIS (see address given above).

NCEER-88-0011 "Seismic Floor Response Spectra for a Combined System by Green's Functions," by F.M. Lavelle, L.A. Bergman and P.D. Spanos, 5/1/88, (PB89-102875, A03, MF-A01).

NCEER-88-0012 "A New Solution Technique for Randomly Excited Hysteretic Structures," by G.Q. Cai and Y.K. Lin, 5/16/88, (PB89-102883, A03, MF-A01).

NCEER-88-0013 "A Study of Radiation Damping and Soil-Structure Interaction Effects in the Centrifuge," by K. Weissman, supervised by J.H. Prevost, 5/24/88, (PB89-144703, A06, MF-A01).

NCEER-88-0014 "Parameter Identification and Implementation of a Kinematic Plasticity Model for Frictional Soils," by J.H. Prevost and D.V. Griffiths, to be published.

NCEER-88-0015 "Two- and Three- Dimensional Dynamic Finite Element Analyses of the Long Valley Dam," by D.V. Griffiths and J.H. Prevost, 6/17/88, (PB89-144711, A04, MF-A01).

NCEER-88-0016 "Damage Assessment of Reinforced Concrete Structures in Eastern United States," by A.M. Reinhorn, M.J. Seidel, S.K. Kunnath and Y.J. Park, 6/15/88, (PB89-122220, A04, MF-A01). This report is only available through NTIS (see address given above).

NCEER-88-0017 "Dynamic Compliance of Vertically Loaded Strip Foundations in Multilayered Viscoelastic Soils," by S. Ahmad and A.S.M. Israil, 6/17/88, (PB89-102891, A04, MF-A01).

NCEER-88-0018 "An Experimental Study of Seismic Structural Response With Added Viscoelastic Dampers," by R.C. Lin, Z. Liang, T.T. Soong and R.H. Zhang, 6/30/88, (PB89-122212, A05, MF-A01). This report is available only through NTIS (see address given above).

NCEER-88-0019 "Experimental Investigation of Primary - Secondary System Interaction," by G.D. Manolis, G. Juhn and A.M. Reinhorn, 5/27/88, (PB89-122204, A04, MF-A01).

NCEER-88-0020 "A Response Spectrum Approach For Analysis of Nonclassically Damped Structures," by J.N. Yang, S. Sarkani and F.X. Long, 4/22/88, (PB89-102909, A04, MF-A01).

NCEER-88-0021 "Seismic Interaction of Structures and Soils: Stochastic Approach," by A.S. Veletsos and A.M. Prasad, 7/21/88, (PB89-122196, A04, MF-A01). This report is only available through NTIS (see address given above).

NCEER-88-0022 "Identification of the Serviceability Limit State and Detection of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 6/15/88, (PB89-122188, A05, MF-A01). This report is available only through NTIS (see address given above).

NCEER-88-0023 "Multi-Hazard Risk Analysis: Case of a Simple Offshore Structure," by B.K. Bhartia and E.H. Vanmarcke, 7/21/88, (PB89-145213, A05, MF-A01).

NCEER-88-0024 "Automated Seismic Design of Reinforced Concrete Buildings," by Y.S. Chung, C. Meyer and M. Shinozuka, 7/5/88, (PB89-122170, A06, MF-A01). This report is available only through NTIS (see address given above).

NCEER-88-0025 "Experimental Study of Active Control of MDOF Structures Under Seismic Excitations," by L.L. Chung, R.C. Lin, T.T. Soong and A.M. Reinhorn, 7/10/88, (PB89-122600, A04, MF-A01).

NCEER-88-0026 "Earthquake Simulation Tests of a Low-Rise Metal Structure," by J.S. Hwang, K.C. Chang, G.C. Lee and R.L. Ketter, 8/1/88, (PB89-102917, A04, MF-A01).

NCEER-88-0027 "Systems Study of Urban Response and Reconstruction Due to Catastrophic Earthquakes," by F. Kozin and H.K. Zhou, 9/22/88, (PB90-162348, A04, MF-A01).

NCEER-88-0028 "Seismic Fragility Analysis of Plane Frame Structures," by H.H-M. Hwang and Y.K. Low, 7/31/88, (PB89-131445, A06, MF-A01).

NCEER-88-0029 "Response Analysis of Stochastic Structures," by A. Kardara, C. Bucher and M. Shinozuka, 9/22/88, (PB89-174429, A04, MF-A01).

NCEER-88-0030 "Nonnormal Accelerations Due to Yielding in a Primary Structure," by D.C.K. Chen and L.D. Lutes, 9/19/88, (PB89-131437, A04, MF-A01).

NCEER-88-0031 "Design Approaches for Soil-Structure Interaction," by A.S. Veletsos, A.M. Prasad and Y. Tang, 12/30/88, (PB89-174437, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-88-0032 "A Re-evaluation of Design Spectra for Seismic Damage Control," by C.J. Turkstra and A.G. Tallin, 11/7/88, (PB89-145221, A05, MF-A01).

NCEER-88-0033 "The Behavior and Design of Noncontact Lap Splices Subjected to Repeated Inelastic Tensile Loading," by V.E. Sagan, P. Gergely and R.N. White, 12/8/88, (PB89-163737, A08, MF-A01).

NCEER-88-0034 "Seismic Response of Pile Foundations," by S.M. Mamoon, P.K. Banerjee and S. Ahmad, 11/1/88, (PB89-145239, A04, MF-A01).

NCEER-88-0035 "Modeling of R/C Building Structures With Flexible Floor Diaphragms (IDARC2)," by A.M. Reinhorn, S.K. Kunnath and N. Panahshahi, 9/7/88, (PB89-207153, A07, MF-A01).

NCEER-88-0036 "Solution of the Dam-Reservoir Interaction Problem Using a Combination of FEM, BEM with Particular Integrals, Modal Analysis, and Substructuring," by C-S. Tsai, G.C. Lee and R.L. Ketter, 12/31/88, (PB89-207146, A04, MF-A01).

NCEER-88-0037 "Optimal Placement of Actuators for Structural Control," by F.Y. Cheng and C.P. Pantelides, 8/15/88, (PB89-162846, A05, MF-A01).

NCEER-88-0038 "Teflon Bearings in Aseismic Base Isolation: Experimental Studies and Mathematical Modeling," by A. Mokha, M.C. Constantinou and A.M. Reinhorn, 12/5/88, (PB89-218457, A10, MF-A01). This report is available only through NTIS (see address given above).

NCEER-88-0039 "Seismic Behavior of Flat Slab High-Rise Buildings in the New York City Area," by P. Weidlinger and M. Ettouney, 10/15/88, (PB90-145681, A04, MF-A01).

NCEER-88-0040 "Evaluation of the Earthquake Resistance of Existing Buildings in New York City," by P. Weidlinger and M. Ettouney, 10/15/88, to be published.

NCEER-88-0041 "Small-Scale Modeling Techniques for Reinforced Concrete Structures Subjected to Seismic Loads," by W. Kim, A. El-Attar and R.N. White, 11/22/88, (PB89-189625, A05, MF-A01).

NCEER-88-0042 "Modeling Strong Ground Motion from Multiple Event Earthquakes," by G.W. Ellis and A.S. Cakmak, 10/15/88, (PB89-174445, A03, MF-A01).

NCEER-88-0043 "Nonstationary Models of Seismic Ground Acceleration," by M. Grigoriu, S.E. Ruiz and E. Rosenblueth, 7/15/88, (PB89-189617, A04, MF-A01).

NCEER-88-0044 "SARCF User's Guide: Seismic Analysis of Reinforced Concrete Frames," by Y.S. Chung, C. Meyer and M. Shinozuka, 11/9/88, (PB89-174452, A08, MF-A01).

NCEER-88-0045 "First Expert Panel Meeting on Disaster Research and Planning," edited by J. Pantelic and J. Stoyle, 9/15/88, (PB89-174460, A05, MF-A01).

NCEER-88-0046 "Preliminary Studies of the Effect of Degrading Infill Walls on the Nonlinear Seismic Response of Steel Frames," by C.Z. Chrysostomou, P. Gergely and J.F. Abel, 12/19/88, (PB89-208383, A05, MF-A01).

NCEER-88-0047 "Reinforced Concrete Frame Component Testing Facility - Design, Construction, Instrumentation and Operation," by S.P. Pessiki, C. Conley, T. Bond, P. Gergely and R.N. White, 12/16/88, (PB89-174478, A04, MF-A01).

NCEER-89-0001 "Effects of Protective Cushion and Soil Compliancy on the Response of Equipment Within a Seismically Excited Building," by J.A. HoLung, 2/16/89, (PB89-207179, A04, MF-A01).

NCEER-89-0002 "Statistical Evaluation of Response Modification Factors for Reinforced Concrete Structures," by H.H-M. Hwang and J-W. Jaw, 2/17/89, (PB89-207187, A05, MF-A01).

NCEER-89-0003 "Hysteretic Columns Under Random Excitation," by G-Q. Cai and Y.K. Lin, 1/9/89, (PB89-196513, A03, MF-A01).

NCEER-89-0004 "Experimental Study of `Elephant Foot Bulge' Instability of Thin-Walled Metal Tanks," by Z-H. Jia and R.L. Ketter, 2/22/89, (PB89-207195, A03, MF-A01).

NCEER-89-0005 "Experiment on Performance of Buried Pipelines Across San Andreas Fault," by J. Isenberg, E. Richardson and T.D. O'Rourke, 3/10/89, (PB89-218440, A04, MF-A01). This report is available only through NTIS (see address given above).

NCEER-89-0006 "A Knowledge-Based Approach to Structural Design of Earthquake-Resistant Buildings," by M. Subramani, P. Gergely, C.H. Conley, J.F. Abel and A.H. Zaghw, 1/15/89, (PB89-218465, A06, MF-A01).

NCEER-89-0007 "Liquefaction Hazards and Their Effects on Buried Pipelines," by T.D. O'Rourke and P.A. Lane, 2/1/89, (PB89-218481, A09, MF-A01).

NCEER-89-0008 "Fundamentals of System Identification in Structural Dynamics," by H. Imai, C-B. Yun, O. Maruyama and M. Shinozuka, 1/26/89, (PB89-207211, A04, MF-A01).

NCEER-89-0009 "Effects of the 1985 Michoacan Earthquake on Water Systems and Other Buried Lifelines in Mexico," by A.G. Ayala and M.J. O'Rourke, 3/8/89, (PB89-207229, A06, MF-A01).

NCEER-89-R010 "NCEER Bibliography of Earthquake Education Materials," by K.E.K. Ross, Second Revision, 9/1/89, (PB90-125352, A05, MF-A01). This report is replaced by NCEER-92-0018.

NCEER-89-0011 "Inelastic Three-Dimensional Response Analysis of Reinforced Concrete Building Structures (IDARC-3D), Part I - Modeling," by S.K. Kunnath and A.M. Reinhorn, 4/17/89, (PB90-114612, A07, MF-A01). This report is available only through NTIS (see address given above).

NCEER-89-0012 "Recommended Modifications to ATC-14," by C.D. Poland and J.O. Malley, 4/12/89, (PB90-108648, A15, MF-A01).

NCEER-89-0013 "Repair and Strengthening of Beam-to-Column Connections Subjected to Earthquake Loading," by M. Corazao and A.J. Durrani, 2/28/89, (PB90-109885, A06, MF-A01).

NCEER-89-0014 "Program EXKAL2 for Identification of Structural Dynamic Systems," by O. Maruyama, C-B. Yun, M. Hoshiya and M. Shinozuka, 5/19/89, (PB90-109877, A09, MF-A01).

NCEER-89-0015 "Response of Frames With Bolted Semi-Rigid Connections, Part I - Experimental Study and Analytical Predictions," by P.J. DiCorso, A.M. Reinhorn, J.R. Dickerson, J.B. Radziminski and W.L. Harper, 6/1/89, to be published.

NCEER-89-0016 "ARMA Monte Carlo Simulation in Probabilistic Structural Analysis," by P.D. Spanos and M.P. Mignolet, 7/10/89, (PB90-109893, A03, MF-A01).

NCEER-89-P017 "Preliminary Proceedings from the Conference on Disaster Preparedness - The Place of Earthquake Education in Our Schools," Edited by K.E.K. Ross, 6/23/89, (PB90-108606, A03, MF-A01).

NCEER-89-0017 "Proceedings from the Conference on Disaster Preparedness - The Place of Earthquake Education in Our Schools," Edited by K.E.K. Ross, 12/31/89, (PB90-207895, A012, MF-A02). This report is available only through NTIS (see address given above).

NCEER-89-0018 "Multidimensional Models of Hysteretic Material Behavior for Vibration Analysis of Shape Memory Energy Absorbing Devices, by E.J. Graesser and F.A. Cozzarelli, 6/7/89, (PB90-164146, A04, MF-A01).

NCEER-89-0019 "Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures (3D-BASIS)," by S. Nagarajaiah, A.M. Reinhorn and M.C. Constantinou, 8/3/89, (PB90-161936, A06, MF-A01). This report has been replaced by NCEER-93-0011.

NCEER-89-0020 "Structural Control Considering Time-Rate of Control Forces and Control Rate Constraints," by F.Y. Cheng and C.P. Pantelides, 8/3/89, (PB90-120445, A04, MF-A01).

NCEER-89-0021 "Subsurface Conditions of Memphis and Shelby County," by K.W. Ng, T-S. Chang and H-H.M. Hwang, 7/26/89, (PB90-120437, A03, MF-A01).

NCEER-89-0022 "Seismic Wave Propagation Effects on Straight Jointed Buried Pipelines," by K. Elhmadi and M.J. O'Rourke, 8/24/89, (PB90-162322, A10, MF-A02).

NCEER-89-0023 "Workshop on Serviceability Analysis of Water Delivery Systems," edited by M. Grigoriu, 3/6/89, (PB90-127424, A03, MF-A01).

NCEER-89-0024 "Shaking Table Study of a 1/5 Scale Steel Frame Composed of Tapered Members," by K.C. Chang, J.S. Hwang and G.C. Lee, 9/18/89, (PB90-160169, A04, MF-A01).

NCEER-89-0025 "DYNA1D: A Computer Program for Nonlinear Seismic Site Response Analysis - Technical Documentation," by Jean H. Prevost, 9/14/89, (PB90-161944, A07, MF-A01). This report is available only through NTIS (see address given above).

NCEER-89-0026 "1:4 Scale Model Studies of Active Tendon Systems and Active Mass Dampers for Aseismic Protection," by A.M. Reinhorn, T.T. Soong, R.C. Lin, Y.P. Yang, Y. Fukao, H. Abe and M. Nakai, 9/15/89, (PB90-173246, A10, MF-A02). This report is available only through NTIS (see address given above).

NCEER-89-0027 "Scattering of Waves by Inclusions in a Nonhomogeneous Elastic Half Space Solved by Boundary Element Methods," by P.K. Hadley, A. Askar and A.S. Cakmak, 6/15/89, (PB90-145699, A07, MF-A01).

NCEER-89-0028 "Statistical Evaluation of Deflection Amplification Factors for Reinforced Concrete Structures," by H.H.M. Hwang, J-W. Jaw and A.L. Ch'ng, 8/31/89, (PB90-164633, A05, MF-A01).

NCEER-89-0029 "Bedrock Accelerations in Memphis Area Due to Large New Madrid Earthquakes," by H.H.M. Hwang, C.H.S. Chen and G. Yu, 11/7/89, (PB90-162330, A04, MF-A01).

NCEER-89-0030 "Seismic Behavior and Response Sensitivity of Secondary Structural Systems," by Y.Q. Chen and T.T. Soong, 10/23/89, (PB90-164658, A08, MF-A01).

NCEER-89-0031 "Random Vibration and Reliability Analysis of Primary-Secondary Structural Systems," by Y. Ibrahim, M. Grigoriu and T.T. Soong, 11/10/89, (PB90-161951, A04, MF-A01).

NCEER-89-0032 "Proceedings from the Second U.S. - Japan Workshop on Liquefaction, Large Ground Deformation and Their Effects on Lifelines, September 26-29, 1989," Edited by T.D. O'Rourke and M. Hamada, 12/1/89, (PB90-209388, A22, MF-A03).

NCEER-89-0033 "Deterministic Model for Seismic Damage Evaluation of Reinforced Concrete Structures," by J.M. Bracci, A.M. Reinhorn, J.B. Mander and S.K. Kunnath, 9/27/89, (PB91-108803, A06, MF-A01).

NCEER-89-0034 "On the Relation Between Local and Global Damage Indices," by E. DiPasquale and A.S. Cakmak, 8/15/89, (PB90-173865, A05, MF-A01).

NCEER-89-0035 "Cyclic Undrained Behavior of Nonplastic and Low Plasticity Silts," by A.J. Walker and H.E. Stewart, 7/26/89, (PB90-183518, A10, MF-A01).

NCEER-89-0036 "Liquefaction Potential of Surficial Deposits in the City of Buffalo, New York," by M. Budhu, R. Giese and L. Baumgrass, 1/17/89, (PB90-208455, A04, MF-A01).

NCEER-89-0037 "A Deterministic Assessment of Effects of Ground Motion Incoherence," by A.S. Veletsos and Y. Tang, 7/15/89, (PB90-164294, A03, MF-A01).

NCEER-89-0038 "Workshop on Ground Motion Parameters for Seismic Hazard Mapping," July 17-18, 1989, edited by R.V. Whitman, 12/1/89, (PB90-173923, A04, MF-A01).

NCEER-89-0039 "Seismic Effects on Elevated Transit Lines of the New York City Transit Authority," by C.J. Costantino, C.A. Miller and E. Heymsfield, 12/26/89, (PB90-207887, A06, MF-A01).

NCEER-89-0040 "Centrifugal Modeling of Dynamic Soil-Structure Interaction," by K. Weissman, Supervised by J.H. Prevost, 5/10/89, (PB90-207879, A07, MF-A01).

NCEER-89-0041 "Linearized Identification of Buildings With Cores for Seismic Vulnerability Assessment," by I-K. Ho and A.E. Aktan, 11/1/89, (PB90-251943, A07, MF-A01).

NCEER-90-0001 "Geotechnical and Lifeline Aspects of the October 17, 1989 Loma Prieta Earthquake in San Francisco," by T.D. O'Rourke, H.E. Stewart, F.T. Blackburn and T.S. Dickerman, 1/90, (PB90-208596, A05, MF-A01).

NCEER-90-0002 "Nonnormal Secondary Response Due to Yielding in a Primary Structure," by D.C.K. Chen and L.D. Lutes, 2/28/90, (PB90-251976, A07, MF-A01).

NCEER-90-0003 "Earthquake Education Materials for Grades K-12," by K.E.K. Ross, 4/16/90, (PB91-251984, A05, MF-A05). This report has been replaced by NCEER-92-0018.

NCEER-90-0004 "Catalog of Strong Motion Stations in Eastern North America," by R.W. Busby, 4/3/90, (PB90-251984, A05, MF-A01).

NCEER-90-0005 "NCEER Strong-Motion Data Base: A User Manual for the GeoBase Release (Version 1.0 for the Sun3)," by P. Friberg and K. Jacob, 3/31/90 (PB90-258062, A04, MF-A01).

NCEER-90-0006 "Seismic Hazard Along a Crude Oil Pipeline in the Event of an 1811-1812 Type New Madrid Earthquake," by H.H.M. Hwang and C-H.S. Chen, 4/16/90, (PB90-258054, A04, MF-A01).

NCEER-90-0007 "Site-Specific Response Spectra for Memphis Sheahan Pumping Station," by H.H.M. Hwang and C.S. Lee, 5/15/90, (PB91-108811, A05, MF-A01).

NCEER-90-0008 "Pilot Study on Seismic Vulnerability of Crude Oil Transmission Systems," by T. Ariman, R. Dobry, M. Grigoriu, F. Kozin, M. O'Rourke, T. O'Rourke and M. Shinozuka, 5/25/90, (PB91-108837, A06, MF-A01).

NCEER-90-0009 "A Program to Generate Site Dependent Time Histories: EQGEN," by G.W. Ellis, M. Srinivasan and A.S. Cakmak, 1/30/90, (PB91-108829, A04, MF-A01).

NCEER-90-0010 "Active Isolation for Seismic Protection of Operating Rooms," by M.E. Talbott, Supervised by M. Shinozuka, 6/8/9, (PB91-110205, A05, MF-A01).

NCEER-90-0011 "Program LINEARID for Identification of Linear Structural Dynamic Systems," by C-B. Yun and M. Shinozuka, 6/25/90, (PB91-110312, A08, MF-A01).

NCEER-90-0012 "Two-Dimensional Two-Phase Elasto-Plastic Seismic Response of Earth Dams," by A.N. Yiagos, Supervised by J.H. Prevost, 6/20/90, (PB91-110197, A13, MF-A02).

NCEER-90-0013 "Secondary Systems in Base-Isolated Structures: Experimental Investigation, Stochastic Response and Stochastic Sensitivity," by G.D. Manolis, G. Juhn, M.C. Constantinou and A.M. Reinhorn, 7/1/90, (PB91-110320, A08, MF-A01).

NCEER-90-0014 "Seismic Behavior of Lightly-Reinforced Concrete Column and Beam-Column Joint Details," by S.P. Pessiki, C.H. Conley, P. Gergely and R.N. White, 8/22/90, (PB91-108795, A11, MF-A02).

NCEER-90-0015 "Two Hybrid Control Systems for Building Structures Under Strong Earthquakes," by J.N. Yang and A. Danielians, 6/29/90, (PB91-125393, A04, MF-A01).

NCEER-90-0016 "Instantaneous Optimal Control with Acceleration and Velocity Feedback," by J.N. Yang and Z. Li, 6/29/90, (PB91-125401, A03, MF-A01).

NCEER-90-0017 "Reconnaissance Report on the Northern Iran Earthquake of June 21, 1990," by M. Mehrain, 10/4/90, (PB91-125377, A03, MF-A01).

NCEER-90-0018 "Evaluation of Liquefaction Potential in Memphis and Shelby County," by T.S. Chang, P.S. Tang, C.S. Lee and H. Hwang, 8/10/90, (PB91-125427, A09, MF-A01).

NCEER-90-0019 "Experimental and Analytical Study of a Combined Sliding Disc Bearing and Helical Steel Spring Isolation System," by M.C. Constantinou, A.S. Mokha and A.M. Reinhorn, 10/4/90, (PB91-125385, A06, MF-A01). This report is available only through NTIS (see address given above).

NCEER-90-0020 "Experimental Study and Analytical Prediction of Earthquake Response of a Sliding Isolation System with a Spherical Surface," by A.S. Mokha, M.C. Constantinou and A.M. Reinhorn, 10/11/90, (PB91-125419, A05, MF-A01).

NCEER-90-0021 "Dynamic Interaction Factors for Floating Pile Groups," by G. Gazetas, K. Fan, A. Kaynia and E. Kausel, 9/10/90, (PB91-170381, A05, MF-A01).

NCEER-90-0022 "Evaluation of Seismic Damage Indices for Reinforced Concrete Structures," by S. Rodriguez-Gomez and A.S. Cakmak, 9/30/90, PB91-171322, A06, MF-A01).

NCEER-90-0023 "Study of Site Response at a Selected Memphis Site," by H. Desai, S. Ahmad, E.S. Gazetas and M.R. Oh, 10/11/90, (PB91-196857, A03, MF-A01).

NCEER-90-0024 "A User's Guide to Strongmo: Version 1.0 of NCEER's Strong-Motion Data Access Tool for PCs and Terminals," by P.A. Friberg and C.A.T. Susch, 11/15/90, (PB91-171272, A03, MF-A01).

NCEER-90-0025 "A Three-Dimensional Analytical Study of Spatial Variability of Seismic Ground Motions," by L-L. Hong and A.H.-S. Ang, 10/30/90, (PB91-170399, A09, MF-A01).

NCEER-90-0026 "MUMOID User's Guide - A Program for the Identification of Modal Parameters," by S. Rodriguez-Gomez and E. DiPasquale, 9/30/90, (PB91-171298, A04, MF-A01).

NCEER-90-0027 "SARCF-II User's Guide - Seismic Analysis of Reinforced Concrete Frames," by S. Rodriguez-Gomez, Y.S. Chung and C. Meyer, 9/30/90, (PB91-171280, A05, MF-A01).

NCEER-90-0028 "Viscous Dampers: Testing, Modeling and Application in Vibration and Seismic Isolation," by N. Makris and M.C. Constantinou, 12/20/90 (PB91-190561, A06, MF-A01).

NCEER-90-0029 "Soil Effects on Earthquake Ground Motions in the Memphis Area," by H. Hwang, C.S. Lee, K.W. Ng and T.S. Chang, 8/2/90, (PB91-190751, A05, MF-A01).

NCEER-91-0001 "Proceedings from the Third Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, December 17-19, 1990," edited by T.D. O'Rourke and M. Hamada, 2/1/91, (PB91-179259, A99, MF-A04).

NCEER-91-0002 "Physical Space Solutions of Non-Proportionally Damped Systems," by M. Tong, Z. Liang and G.C. Lee, 1/15/91, (PB91-179242, A04, MF-A01).

NCEER-91-0003 "Seismic Response of Single Piles and Pile Groups," by K. Fan and G. Gazetas, 1/10/91, (PB92-174994, A04, MF-A01).

NCEER-91-0004 "Damping of Structures: Part 1 - Theory of Complex Damping," by Z. Liang and G. Lee, 10/10/91, (PB92-197235, A12, MF-A03).

NCEER-91-0005 "3D-BASIS - Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures: Part II," by S. Nagarajaiah, A.M. Reinhorn and M.C. Constantinou, 2/28/91, (PB91-190553, A07, MF-A01). This report has been replaced by NCEER-93-0011.

NCEER-91-0006 "A Multidimensional Hysteretic Model for Plasticity Deforming Metals in Energy Absorbing Devices," by E.J. Graesser and F.A. Cozzarelli, 4/9/91, (PB92-108364, A04, MF-A01).

NCEER-91-0007 "A Framework for Customizable Knowledge-Based Expert Systems with an Application to a KBES for Evaluating the Seismic Resistance of Existing Buildings," by E.G. Ibarra-Anaya and S.J. Fenves, 4/9/91, (PB91-210930, A08, MF-A01).

NCEER-91-0008 "Nonlinear Analysis of Steel Frames with Semi-Rigid Connections Using the Capacity Spectrum Method," by G.G. Deierlein, S-H. Hsieh, Y-J. Shen and J.F. Abel, 7/2/91, (PB92-113828, A05, MF-A01).

NCEER-91-0009 "Earthquake Education Materials for Grades K-12," by K.E.K. Ross, 4/30/91, (PB91-212142, A06, MF-A01). This report has been replaced by NCEER-92-0018.

NCEER-91-0010 "Phase Wave Velocities and Displacement Phase Differences in a Harmonically Oscillating Pile," by N. Makris and G. Gazetas, 7/8/91, (PB92-108356, A04, MF-A01).

NCEER-91-0011 "Dynamic Characteristics of a Full-Size Five-Story Steel Structure and a 2/5 Scale Model," by K.C. Chang, G.C. Yao, G.C. Lee, D.S. Hao and Y.C. Yeh," 7/2/91, (PB93-116648, A06, MF-A02).

NCEER-91-0012 "Seismic Response of a 2/5 Scale Steel Structure with Added Viscoelastic Dampers," by K.C. Chang, T.T. Soong, S-T. Oh and M.L. Lai, 5/17/91, (PB92-110816, A05, MF-A01).

NCEER-91-0013 "Earthquake Response of Retaining Walls; Full-Scale Testing and Computational Modeling," by S. Alampalli and A-W.M. Elgamal, 6/20/91, to be published.

NCEER-91-0014 "3D-BASIS-M: Nonlinear Dynamic Analysis of Multiple Building Base Isolated Structures," by P.C. Tsopelas, S. Nagarajaiah, M.C. Constantinou and A.M. Reinhorn, 5/28/91, (PB92-113885, A09, MF-A02).

NCEER-91-0015 "Evaluation of SEAOC Design Requirements for Sliding Isolated Structures," by D. Theodossiou and M.C. Constantinou, 6/10/91, (PB92-114602, A11, MF-A03).

NCEER-91-0016 "Closed-Loop Modal Testing of a 27-Story Reinforced Concrete Flat Plate-Core Building," by H.R. Somaprasad, T. Toksoy, H. Yoshiyuki and A.E. Aktan, 7/15/91, (PB92-129980, A07, MF-A02).

NCEER-91-0017 "Shake Table Test of a 1/6 Scale Two-Story Lightly Reinforced Concrete Building," by A.G. El-Attar, R.N. White and P. Gergely, 2/28/91, (PB92-222447, A06, MF-A02).

NCEER-91-0018 "Shake Table Test of a 1/8 Scale Three-Story Lightly Reinforced Concrete Building," by A.G. El-Attar, R.N. White and P. Gergely, 2/28/91, (PB93-116630, A08, MF-A02).

NCEER-91-0019 "Transfer Functions for Rigid Rectangular Foundations," by A.S. Veletsos, A.M. Prasad and W.H. Wu, 7/31/91, to be published.

NCEER-91-0020 "Hybrid Control of Seismic-Excited Nonlinear and Inelastic Structural Systems," by J.N. Yang, Z. Li and A. Danielians, 8/1/91, (PB92-143171, A06, MF-A02).

NCEER-91-0021 "The NCEER-91 Earthquake Catalog: Improved Intensity-Based Magnitudes and Recurrence Relations for U.S. Earthquakes East of New Madrid," by L. Seeber and J.G. Armbruster, 8/28/91, (PB92-176742, A06, MF-A02).

NCEER-91-0022 "Proceedings from the Implementation of Earthquake Planning and Education in Schools: The Need for Change - The Roles of the Changemakers," by K.E.K. Ross and F. Winslow, 7/23/91, (PB92-129998, A12, MF-A03).

NCEER-91-0023 "A Study of Reliability-Based Criteria for Seismic Design of Reinforced Concrete Frame Buildings," by H.H.M. Hwang and H-M. Hsu, 8/10/91, (PB92-140235, A09, MF-A02).

NCEER-91-0024 "Experimental Verification of a Number of Structural System Identification Algorithms," by R.G. Ghanem, H. Gavin and M. Shinozuka, 9/18/91, (PB92-176577, A18, MF-A04).

NCEER-91-0025 "Probabilistic Evaluation of Liquefaction Potential," by H.H.M. Hwang and C.S. Lee," 11/25/91, (PB92-143429, A05, MF-A01).

NCEER-91-0026 "Instantaneous Optimal Control for Linear, Nonlinear and Hysteretic Structures - Stable Controllers," by J.N. Yang and Z. Li, 11/15/91, (PB92-163807, A04, MF-A01).

NCEER-91-0027 "Experimental and Theoretical Study of a Sliding Isolation System for Bridges," by M.C. Constantinou, A. Kartoum, A.M. Reinhorn and P. Bradford, 11/15/91, (PB92-176973, A10, MF-A03).

NCEER-92-0001 "Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes, Volume 1: Japanese Case Studies," Edited by M. Hamada and T. O'Rourke, 2/17/92, (PB92-197243, A18, MF-A04).

NCEER-92-0002 "Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes, Volume 2: United States Case Studies," Edited by T. O'Rourke and M. Hamada, 2/17/92, (PB92-197250, A20, MF-A04).

NCEER-92-0003 "Issues in Earthquake Education," Edited by K. Ross, 2/3/92, (PB92-222389, A07, MF-A02).

NCEER-92-0004 "Proceedings from the First U.S. - Japan Workshop on Earthquake Protective Systems for Bridges," Edited by I.G. Buckle, 2/4/92, (PB94-142239, A99, MF-A06).

NCEER-92-0005 "Seismic Ground Motion from a Haskell-Type Source in a Multiple-Layered Half-Space," A.P. Theoharis, G. Deodatis and M. Shinozuka, 1/2/92, to be published.

NCEER-92-0006 "Proceedings from the Site Effects Workshop," Edited by R. Whitman, 2/29/92, (PB92-197201, A04, MF-A01).

NCEER-92-0007 "Engineering Evaluation of Permanent Ground Deformations Due to Seismically-Induced Liquefaction," by M.H. Baziar, R. Dobry and A-W.M. Elgamal, 3/24/92, (PB92-222421, A13, MF-A03).

NCEER-92-0008 "A Procedure for the Seismic Evaluation of Buildings in the Central and Eastern United States," by C.D. Poland and J.O. Malley, 4/2/92, (PB92-222439, A20, MF-A04).

NCEER-92-0009 "Experimental and Analytical Study of a Hybrid Isolation System Using Friction Controllable Sliding Bearings," by M.Q. Feng, S. Fujii and M. Shinozuka, 5/15/92, (PB93-150282, A06, MF-A02).

NCEER-92-0010 "Seismic Resistance of Slab-Column Connections in Existing Non-Ductile Flat-Plate Buildings," by A.J. Durrani and Y. Du, 5/18/92, (PB93-116812, A06, MF-A02).

NCEER-92-0011 "The Hysteretic and Dynamic Behavior of Brick Masonry Walls Upgraded by Ferrocement Coatings Under Cyclic Loading and Strong Simulated Ground Motion," by H. Lee and S.P. Prawel, 5/11/92, to be published.

NCEER-92-0012 "Study of Wire Rope Systems for Seismic Protection of Equipment in Buildings," by G.F. Demetriades, M.C. Constantinou and A.M. Reinhorn, 5/20/92, (PB93-116655, A08, MF-A02).

NCEER-92-0013 "Shape Memory Structural Dampers: Material Properties, Design and Seismic Testing," by P.R. Witting and F.A. Cozzarelli, 5/26/92, (PB93-116663, A05, MF-A01).

NCEER-92-0014 "Longitudinal Permanent Ground Deformation Effects on Buried Continuous Pipelines," by M.J. O'Rourke, and C. Nordberg, 6/15/92, (PB93-116671, A08, MF-A02).

NCEER-92-0015 "A Simulation Method for Stationary Gaussian Random Functions Based on the Sampling Theorem," by M. Grigoriu and S. Balopoulou, 6/11/92, (PB93-127496, A05, MF-A01).

NCEER-92-0016 "Gravity-Load-Designed Reinforced Concrete Buildings: Seismic Evaluation of Existing Construction and Detailing Strategies for Improved Seismic Resistance," by G.W. Hoffmann, S.K. Kunnath, A.M. Reinhorn and J.B. Mander, 7/15/92, (PB94-142007, A08, MF-A02).

NCEER-92-0017 "Observations on Water System and Pipeline Performance in the Limón Area of Costa Rica Due to the April 22, 1991 Earthquake," by M. O'Rourke and D. Ballantyne, 6/30/92, (PB93-126811, A06, MF-A02).

NCEER-92-0018 "Fourth Edition of Earthquake Education Materials for Grades K-12," Edited by K.E.K. Ross, 8/10/92, (PB93-114023, A07, MF-A02).

NCEER-92-0019 "Proceedings from the Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction," Edited by M. Hamada and T.D. O'Rourke, 8/12/92, (PB93-163939, A99, MF-E11).

NCEER-92-0020 "Active Bracing System: A Full Scale Implementation of Active Control," by A.M. Reinhorn, T.T. Soong, R.C. Lin, M.A. Riley, Y.P. Wang, S. Aizawa and M. Higashino, 8/14/92, (PB93-127512, A06, MF-A02).

NCEER-92-0021 "Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-Induced Lateral Spreads," by S.F. Bartlett and T.L. Youd, 8/17/92, (PB93-188241, A06, MF-A02).

NCEER-92-0022 "IDARC Version 3.0: Inelastic Damage Analysis of Reinforced Concrete Structures," by S.K. Kunnath, A.M. Reinhorn and R.F. Lobo, 8/31/92, (PB93-227502, A07, MF-A02).

NCEER-92-0023 "A Semi-Empirical Analysis of Strong-Motion Peaks in Terms of Seismic Source, Propagation Path and Local Site Conditions, by M. Kamiyama, M.J. O'Rourke and R. Flores-Berrones, 9/9/92, (PB93-150266, A08, MF-A02).

NCEER-92-0024 "Seismic Behavior of Reinforced Concrete Frame Structures with Nonductile Details, Part I: Summary of Experimental Findings of Full Scale Beam-Column Joint Tests," by A. Beres, R.N. White and P. Gergely, 9/30/92, (PB93-227783, A05, MF-A01).

NCEER-92-0025 "Experimental Results of Repaired and Retrofitted Beam-Column Joint Tests in Lightly Reinforced Concrete Frame Buildings," by A. Beres, S. El-Borgi, R.N. White and P. Gergely, 10/29/92, (PB93-227791, A05, MF-A01).

NCEER-92-0026 "A Generalization of Optimal Control Theory: Linear and Nonlinear Structures," by J.N. Yang, Z. Li and S. Vongchavalitkul, 11/2/92, (PB93-188621, A05, MF-A01).

NCEER-92-0027 "Seismic Resistance of Reinforced Concrete Frame Structures Designed Only for Gravity Loads: Part I - Design and Properties of a One-Third Scale Model Structure," by J.M. Bracci, A.M. Reinhorn and J.B. Mander, 12/1/92, (PB94-104502, A08, MF-A02).

NCEER-92-0028 "Seismic Resistance of Reinforced Concrete Frame Structures Designed Only for Gravity Loads: Part II - Experimental Performance of Subassemblages," by L.E. Aycardi, J.B. Mander and A.M. Reinhorn, 12/1/92, (PB94-104510, A08, MF-A02).

NCEER-92-0029 "Seismic Resistance of Reinforced Concrete Frame Structures Designed Only for Gravity Loads: Part III - Experimental Performance and Analytical Study of a Structural Model," by J.M. Bracci, A.M. Reinhorn and J.B. Mander, 12/1/92, (PB93-227528, A09, MF-A01).

NCEER-92-0030 "Evaluation of Seismic Retrofit of Reinforced Concrete Frame Structures: Part I - Experimental Performance of Retrofitted Subassemblages," by D. Choudhuri, J.B. Mander and A.M. Reinhorn, 12/8/92, (PB93-198307, A07, MF-A02).

NCEER-92-0031 "Evaluation of Seismic Retrofit of Reinforced Concrete Frame Structures: Part II - Experimental Performance and Analytical Study of a Retrofitted Structural Model," by J.M. Bracci, A.M. Reinhorn and J.B. Mander, 12/8/92, (PB93-198315, A09, MF-A03).

NCEER-92-0032 "Experimental and Analytical Investigation of Seismic Response of Structures with Supplemental Fluid Viscous Dampers," by M.C. Constantinou and M.D. Symans, 12/21/92, (PB93-191435, A10, MF-A03). This report is available only through NTIS (see address given above).

NCEER-92-0033 "Reconnaissance Report on the Cairo, Egypt Earthquake of October 12, 1992," by M. Khater, 12/23/92, (PB93-188621, A03, MF-A01).

NCEER-92-0034 "Low-Level Dynamic Characteristics of Four Tall Flat-Plate Buildings in New York City," by H. Gavin, S. Yuan, J. Grossman, E. Pekelis and K. Jacob, 12/28/92, (PB93-188217, A07, MF-A02).

NCEER-93-0001 "An Experimental Study on the Seismic Performance of Brick-Infilled Steel Frames With and Without Retrofit," by J.B. Mander, B. Nair, K. Wojtkowski and J. Ma, 1/29/93, (PB93-227510, A07, MF-A02).

NCEER-93-0002 "Social Accounting for Disaster Preparedness and Recovery Planning," by S. Cole, E. Pantoja and V. Razak, 2/22/93, (PB94-142114, A12, MF-A03).

NCEER-93-0003 "Assessment of 1991 NEHRP Provisions for Nonstructural Components and Recommended Revisions," by T.T. Soong, G. Chen, Z. Wu, R-H. Zhang and M. Grigoriu, 3/1/93, (PB93-188639, A06, MF-A02).

NCEER-93-0004 "Evaluation of Static and Response Spectrum Analysis Procedures of SEAOC/UBC for Seismic Isolated Structures," by C.W. Winters and M.C. Constantinou, 3/23/93, (PB93-198299, A10, MF-A03).

NCEER-93-0005 "Earthquakes in the Northeast - Are We Ignoring the Hazard? A Workshop on Earthquake Science and Safety for Educators," edited by K.E.K. Ross, 4/2/93, (PB94-103066, A09, MF-A02).

NCEER-93-0006 "Inelastic Response of Reinforced Concrete Structures with Viscoelastic Braces," by R.F. Lobo, J.M. Bracci, K.L. Shen, A.M. Reinhorn and T.T. Soong, 4/5/93, (PB93-227486, A05, MF-A02).

NCEER-93-0007 "Seismic Testing of Installation Methods for Computers and Data Processing Equipment," by K. Kosar, T.T. Soong, K.L. Shen, J.A. HoLung and Y.K. Lin, 4/12/93, (PB93-198299, A07, MF-A02).

NCEER-93-0008 "Retrofit of Reinforced Concrete Frames Using Added Dampers," by A. Reinhorn, M. Constantinou and C. Li, to be published.

NCEER-93-0009 "Seismic Behavior and Design Guidelines for Steel Frame Structures with Added Viscoelastic Dampers," by K.C. Chang, M.L. Lai, T.T. Soong, D.S. Hao and Y.C. Yeh, 5/1/93, (PB94-141959, A07, MF-A02).

NCEER-93-0010 "Seismic Performance of Shear-Critical Reinforced Concrete Bridge Piers," by J.B. Mander, S.M. Waheed, M.T.A. Chaudhary and S.S. Chen, 5/12/93, (PB93-227494, A08, MF-A02).

NCEER-93-0011 "3D-BASIS-TABS: Computer Program for Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures," by S. Nagarajaiah, C. Li, A.M. Reinhorn and M.C. Constantinou, 8/2/93, (PB94-141819, A09, MF-A02).

NCEER-93-0012 "Effects of Hydrocarbon Spills from an Oil Pipeline Break on Ground Water," by O.J. Helweg and H.H.M. Hwang, 8/3/93, (PB94-141942, A06, MF-A02).

NCEER-93-0013 "Simplified Procedures for Seismic Design of Nonstructural Components and Assessment of Current Code Provisions," by M.P. Singh, L.E. Suarez, E.E. Matheu and G.O. Maldonado, 8/4/93, (PB94-141827, A09, MF-A02).

NCEER-93-0014 "An Energy Approach to Seismic Analysis and Design of Secondary Systems," by G. Chen and T.T. Soong, 8/6/93, (PB94-142767, A11, MF-A03).

NCEER-93-0015 "Proceedings from School Sites: Becoming Prepared for Earthquakes - Commemorating the Third Anniversary of the Loma Prieta Earthquake," Edited by F.E. Winslow and K.E.K. Ross, 8/16/93, (PB94-154275, A16, MF-A02).

NCEER-93-0016 "Reconnaissance Report of Damage to Historic Monuments in Cairo, Egypt Following the October 12, 1992 Dahshur Earthquake," by D. Sykora, D. Look, G. Croci, E. Karaesmen and E. Karaesmen, 8/19/93, (PB94-142221, A08, MF-A02).

NCEER-93-0017 "The Island of Guam Earthquake of August 8, 1993," by S.W. Swan and S.K. Harris, 9/30/93, (PB94-141843, A04, MF-A01).

NCEER-93-0018 "Engineering Aspects of the October 12, 1992 Egyptian Earthquake," by A.W. Elgamal, M. Amer, K. Adalier and A. Abul-Fadl, 10/7/93, (PB94-141983, A05, MF-A01).

NCEER-93-0019 "Development of an Earthquake Motion Simulator and its Application in Dynamic Centrifuge Testing," by I. Krstelj, Supervised by J.H. Prevost, 10/23/93, (PB94-181773, A-10, MF-A03).

NCEER-93-0020 "NCEER-Taisei Corporation Research Program on Sliding Seismic Isolation Systems for Bridges: Experimental and Analytical Study of a Friction Pendulum System (FPS)," by M.C. Constantinou, P. Tsopelas, Y-S. Kim and S. Okamoto, 11/1/93, (PB94-142775, A08, MF-A02).

NCEER-93-0021 "Finite Element Modeling of Elastomeric Seismic Isolation Bearings," by L.J. Billings, Supervised by R. Shepherd, 11/8/93, to be published.

NCEER-93-0022 "Seismic Vulnerability of Equipment in Critical Facilities: Life-Safety and Operational Consequences," by K. Porter, G.S. Johnson, M.M. Zadeh, C. Scawthorn and S. Eder, 11/24/93, (PB94-181765, A16, MF-A03).

NCEER-93-0023 "Hokkaido Nansei-oki, Japan Earthquake of July 12, 1993, by P.I. Yanev and C.R. Scawthorn, 12/23/93, (PB94-181500, A07, MF-A01).

NCEER-94-0001 "An Evaluation of Seismic Serviceability of Water Supply Networks with Application to the San Francisco Auxiliary Water Supply System," by I. Markov, Supervised by M. Grigoriu and T. O'Rourke, 1/21/94, (PB94-204013, A07, MF-A02).

NCEER-94-0002 "NCEER-Taisei Corporation Research Program on Sliding Seismic Isolation Systems for Bridges: Experimental and Analytical Study of Systems Consisting of Sliding Bearings, Rubber Restoring Force Devices and Fluid Dampers," Volumes I and II, by P. Tsopelas, S. Okamoto, M.C. Constantinou, D. Ozaki and S. Fujii, 2/4/94, (PB94-181740, A09, MF-A02 and PB94-181757, A12, MF-A03).

NCEER-94-0003 "A Markov Model for Local and Global Damage Indices in Seismic Analysis," by S. Rahman and M. Grigoriu, 2/18/94, (PB94-206000, A12, MF-A03).

NCEER-94-0004 "Proceedings from the NCEER Workshop on Seismic Response of Masonry Infills," edited by D.P. Abrams, 3/1/94, (PB94-180783, A07, MF-A02).

NCEER-94-0005 "The Northridge, California Earthquake of January 17, 1994: General Reconnaissance Report," edited by J.D. Goltz, 3/11/94, (PB94-193943, A10, MF-A03).

NCEER-94-0006 "Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I - Evaluation of Seismic Capacity," by G.A. Chang and J.B. Mander, 3/14/94, (PB94-219185, A11, MF-A03).

NCEER-94-0007 "Seismic Isolation of Multi-Story Frame Structures Using Spherical Sliding Isolation Systems," by T.M. Al-Hussaini, V.A. Zayas and M.C. Constantinou, 3/17/94, (PB94-193745, A09, MF-A02).

NCEER-94-0008 "The Northridge, California Earthquake of January 17, 1994: Performance of Highway Bridges," edited by I.G. Buckle, 3/24/94, (PB94-193851, A06, MF-A02).

NCEER-94-0009 "Proceedings of the Third U.S.-Japan Workshop on Earthquake Protective Systems for Bridges," edited by I.G. Buckle and I. Friedland, 3/31/94, (PB94-195815, A99, MF-A06).

NCEER-94-0010 "3D-BASIS-ME: Computer Program for Nonlinear Dynamic Analysis of Seismically Isolated Single and Multiple Structures and Liquid Storage Tanks," by P.C. Tsopelas, M.C. Constantinou and A.M. Reinhorn, 4/12/94, (PB94-204922, A09, MF-A02).

NCEER-94-0011 "The Northridge, California Earthquake of January 17, 1994: Performance of Gas Transmission Pipelines," by T.D. O'Rourke and M.C. Palmer, 5/16/94, (PB94-204989, A05, MF-A01).

NCEER-94-0012 "Feasibility Study of Replacement Procedures and Earthquake Performance Related to Gas Transmission Pipelines," by T.D. O'Rourke and M.C. Palmer, 5/25/94, (PB94-206638, A09, MF-A02).

NCEER-94-0013 "Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part II - Evaluation of Seismic Demand," by G.A. Chang and J.B. Mander, 6/1/94, (PB95-18106, A08, MF-A02).

NCEER-94-0014 "NCEER-Taisei Corporation Research Program on Sliding Seismic Isolation Systems for Bridges: Experimental and Analytical Study of a System Consisting of Sliding Bearings and Fluid Restoring Force/Damping Devices," by P. Tsopelas and M.C. Constantinou, 6/13/94, (PB94-219144, A10, MF-A03).

NCEER-94-0015 "Generation of Hazard-Consistent Fragility Curves for Seismic Loss Estimation Studies," by H. Hwang and J-R. Huo, 6/14/94, (PB95-181996, A09, MF-A02).

NCEER-94-0016 "Seismic Study of Building Frames with Added Energy-Absorbing Devices," by W.S. Pong, C.S. Tsai and G.C. Lee, 6/20/94, (PB94-219136, A10, A03).

NCEER-94-0017 "Sliding Mode Control for Seismic-Excited Linear and Nonlinear Civil Engineering Structures," by J. Yang, J. Wu, A. Agrawal and Z. Li, 6/21/94, (PB95-138483, A06, MF-A02).

NCEER-94-0018 "3D-BASIS-TABS Version 2.0: Computer Program for Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures," by A.M. Reinhorn, S. Nagarajaiah, M.C. Constantinou, P. Tsopelas and R. Li, 6/22/94, (PB95-182176, A08, MF-A02).

NCEER-94-0019 "Proceedings of the International Workshop on Civil Infrastructure Systems: Application of Intelligent Systems and Advanced Materials on Bridge Systems," Edited by G.C. Lee and K.C. Chang, 7/18/94, (PB95-252474, A20, MF-A04).

NCEER-94-0020 "Study of Seismic Isolation Systems for Computer Floors," by V. Lambrou and M.C. Constantinou, 7/19/94, (PB95-138533, A10, MF-A03).

NCEER-94-0021 "Proceedings of the U.S.-Italian Workshop on Guidelines for Seismic Evaluation and Rehabilitation of Unreinforced Masonry Buildings," Edited by D.P. Abrams and G.M. Calvi, 7/20/94, (PB95-138749, A13, MF-A03).

NCEER-94-0022 "NCEER-Taisei Corporation Research Program on Sliding Seismic Isolation Systems for Bridges: Experimental and Analytical Study of a System Consisting of Lubricated PTFE Sliding Bearings and Mild Steel Dampers," by P. Tsopelas and M.C. Constantinou, 7/22/94, (PB95-182184, A08, MF-A02).

NCEER-94-0023 “Development of Reliability-Based Design Criteria for Buildings Under Seismic Load,” by Y.K. Wen, H. Hwang and M. Shinozuka, 8/1/94, (PB95-211934, A08, MF-A02).

NCEER-94-0024 “Experimental Verification of Acceleration Feedback Control Strategies for an Active Tendon System,” by S.J. Dyke, B.F. Spencer, Jr., P. Quast, M.K. Sain, D.C. Kaspari, Jr. and T.T. Soong, 8/29/94, (PB95-212320, A05, MF-A01).

NCEER-94-0025 “Seismic Retrofitting Manual for Highway Bridges,” Edited by I.G. Buckle and I.F. Friedland, published by the Federal Highway Administration (PB95-212676, A15, MF-A03).

NCEER-94-0026 “Proceedings from the Fifth U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction,” Edited by T.D. O’Rourke and M. Hamada, 11/7/94, (PB95-220802, A99, MF-E08).

NCEER-95-0001 "Experimental and Analytical Investigation of Seismic Retrofit of Structures with Supplemental Damping: Part 1 - Fluid Viscous Damping Devices," by A.M. Reinhorn, C. Li and M.C. Constantinou, 1/3/95, (PB95-266599, A09, MF-A02).

NCEER-95-0002 "Experimental and Analytical Study of Low-Cycle Fatigue Behavior of Semi-Rigid Top-And-Seat Angle Connections," by G. Pekcan, J.B. Mander and S.S. Chen, 1/5/95, (PB95-220042, A07, MF-A02).

NCEER-95-0003 "NCEER-ATC Joint Study on Fragility of Buildings," by T. Anagnos, C. Rojahn and A.S. Kiremidjian, 1/20/95, (PB95-220026, A06, MF-A02).

NCEER-95-0004 "Nonlinear Control Algorithms for Peak Response Reduction," by Z. Wu, T.T. Soong, V. Gattulli and R.C. Lin, 2/16/95, (PB95-220349, A05, MF-A01).

NCEER-95-0005 "Pipeline Replacement Feasibility Study: A Methodology for Minimizing Seismic and Corrosion Risks to Underground Natural Gas Pipelines," by R.T. Eguchi, H.A. Seligson and D.G. Honegger, 3/2/95, (PB95-252326, A06, MF-A02).

NCEER-95-0006 "Evaluation of Seismic Performance of an 11-Story Frame Building During the 1994 Northridge Earthquake," by F. Naeim, R. DiSulio, K. Benuska, A. Reinhorn and C. Li, to be published.

NCEER-95-0007 "Prioritization of Bridges for Seismic Retrofitting," by N. Basöz and A.S. Kiremidjian, 4/24/95, (PB95-252300, A08, MF-A02).

NCEER-95-0008 "Method for Developing Motion Damage Relationships for Reinforced Concrete Frames," by A. Singhal and A.S. Kiremidjian, 5/11/95, (PB95-266607, A06, MF-A02).

NCEER-95-0009 "Experimental and Analytical Investigation of Seismic Retrofit of Structures with Supplemental Damping: Part II - Friction Devices," by C. Li and A.M. Reinhorn, 7/6/95, (PB96-128087, A11, MF-A03).

NCEER-95-0010 "Experimental Performance and Analytical Study of a Non-Ductile Reinforced Concrete Frame Structure Retrofitted with Elastomeric Spring Dampers," by G. Pekcan, J.B. Mander and S.S. Chen, 7/14/95, (PB96-137161, A08, MF-A02).

NCEER-95-0011 "Development and Experimental Study of Semi-Active Fluid Damping Devices for Seismic Protection of Structures," by M.D. Symans and M.C. Constantinou, 8/3/95, (PB96-136940, A23, MF-A04).

NCEER-95-0012 "Real-Time Structural Parameter Modification (RSPM): Development of Innervated Structures," by Z. Liang, M. Tong and G.C. Lee, 4/11/95, (PB96-137153, A06, MF-A01).

NCEER-95-0013 "Experimental and Analytical Investigation of Seismic Retrofit of Structures with Supplemental Damping: Part III - Viscous Damping Walls," by A.M. Reinhorn and C. Li, 10/1/95, (PB96-176409, A11, MF-A03).

NCEER-95-0014 "Seismic Fragility Analysis of Equipment and Structures in a Memphis Electric Substation," by J-R. Huo and H.H.M. Hwang, 8/10/95, (PB96-128087, A09, MF-A02).

NCEER-95-0015 "The Hanshin-Awaji Earthquake of January 17, 1995: Performance of Lifelines," Edited by M. Shinozuka, 11/3/95, (PB96-176383, A15, MF-A03).

NCEER-95-0016 "Highway Culvert Performance During Earthquakes," by T.L. Youd and C.J. Beckman, available as NCEER-96-0015.

NCEER-95-0017 "The Hanshin-Awaji Earthquake of January 17, 1995: Performance of Highway Bridges," Edited by I.G. Buckle, 12/1/95, to be published.

NCEER-95-0018 "Modeling of Masonry Infill Panels for Structural Analysis," by A.M. Reinhorn, A. Madan, R.E. Valles, Y. Reichmann and J.B. Mander, 12/8/95, (PB97-110886, MF-A01, A06).

NCEER-95-0019 "Optimal Polynomial Control for Linear and Nonlinear Structures," by A.K. Agrawal and J.N. Yang, 12/11/95, (PB96-168737, A07, MF-A02).

NCEER-95-0020 "Retrofit of Non-Ductile Reinforced Concrete Frames Using Friction Dampers," by R.S. Rao, P. Gergely and R.N. White, 12/22/95, (PB97-133508, A10, MF-A02).

NCEER-95-0021 "Parametric Results for Seismic Response of Pile-Supported Bridge Bents," by G. Mylonakis, A. Nikolaou and G. Gazetas, 12/22/95, (PB97-100242, A12, MF-A03).

NCEER-95-0022 "Kinematic Bending Moments in Seismically Stressed Piles," by A. Nikolaou, G. Mylonakis and G. Gazetas, 12/23/95, (PB97-113914, MF-A03, A13).

NCEER-96-0001 "Dynamic Response of Unreinforced Masonry Buildings with Flexible Diaphragms," by A.C. Costley and D.P. Abrams," 10/10/96, (PB97-133573, MF-A03, A15).

NCEER-96-0002 "State of the Art Review: Foundations and Retaining Structures," by I. Po Lam, to be published.

NCEER-96-0003 "Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement," by N. Wehbe, M. Saiidi, D. Sanders and B. Douglas, 11/7/96, (PB97-133557, A06, MF-A02).

NCEER-96-0004 "Proceedings of the Long-Span Bridge Seismic Research Workshop," edited by I.G. Buckle and I.M. Friedland, to be published.

NCEER-96-0005 "Establish Representative Pier Types for Comprehensive Study: Eastern United States," by J. Kulicki and Z. Prucz, 5/28/96, (PB98-119217, A07, MF-A02).

NCEER-96-0006 "Establish Representative Pier Types for Comprehensive Study: Western United States," by R. Imbsen, R.A. Schamber and T.A. Osterkamp, 5/28/96, (PB98-118607, A07, MF-A02).

NCEER-96-0007 "Nonlinear Control Techniques for Dynamical Systems with Uncertain Parameters," by R.G. Ghanem and M.I. Bujakov, 5/27/96, (PB97-100259, A17, MF-A03).

NCEER-96-0008 "Seismic Evaluation of a 30-Year Old Non-Ductile Highway Bridge Pier and Its Retrofit," by J.B. Mander, B. Mahmoodzadegan, S. Bhadra and S.S. Chen, 5/31/96, (PB97-110902, MF-A03, A10).

NCEER-96-0009 "Seismic Performance of a Model Reinforced Concrete Bridge Pier Before and After Retrofit," by J.B. Mander, J.H. Kim and C.A. Ligozio, 5/31/96, (PB97-110910, MF-A02, A10).

NCEER-96-0010 "IDARC2D Version 4.0: A Computer Program for the Inelastic Damage Analysis of Buildings," by R.E. Valles, A.M. Reinhorn, S.K. Kunnath, C. Li and A. Madan, 6/3/96, (PB97-100234, A17, MF-A03).

NCEER-96-0011 "Estimation of the Economic Impact of Multiple Lifeline Disruption: Memphis Light, Gas and Water Division Case Study," by S.E. Chang, H.A. Seligson and R.T. Eguchi, 8/16/96, (PB97-133490, A11, MF-A03).

NCEER-96-0012 "Proceedings from the Sixth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Edited by M. Hamada and T. O'Rourke, 9/11/96, (PB97-133581, A99, MF-A06).

NCEER-96-0013 "Chemical Hazards, Mitigation and Preparedness in Areas of High Seismic Risk: A Methodology for Estimating the Risk of Post-Earthquake Hazardous Materials Release," by H.A. Seligson, R.T. Eguchi, K.J. Tierney and K. Richmond, 11/7/96, (PB97-133565, MF-A02, A08).

NCEER-96-0014 "Response of Steel Bridge Bearings to Reversed Cyclic Loading," by J.B. Mander, D-K. Kim, S.S. Chen and G.J. Premus, 11/13/96, (PB97-140735, A12, MF-A03).

NCEER-96-0015 "Highway Culvert Performance During Past Earthquakes," by T.L. Youd and C.J. Beckman, 11/25/96, (PB97-133532, A06, MF-A01).

NCEER-97-0001 "Evaluation, Prevention and Mitigation of Pounding Effects in Building Structures," by R.E. Valles and A.M. Reinhorn, 2/20/97, (PB97-159552, A14, MF-A03).

NCEER-97-0002 "Seismic Design Criteria for Bridges and Other Highway Structures," by C. Rojahn, R. Mayes, D.G. Anderson, J. Clark, J.H. Hom, R.V. Nutt and M.J. O'Rourke, 4/30/97, (PB97-194658, A06, MF-A03).

NCEER-97-0003 “Proceedings of the U.S.-Italian Workshop on Seismic Evaluation and Retrofit,” Edited by D.P. Abrams and G.M. Calvi, 3/19/97, (PB97-194666, A13, MF-A03).

NCEER-97-0004 "Investigation of Seismic Response of Buildings with Linear and Nonlinear Fluid Viscous Dampers," by A.A. Seleemah and M.C. Constantinou, 5/21/97, (PB98-109002, A15, MF-A03).

NCEER-97-0005 "Proceedings of the Workshop on Earthquake Engineering Frontiers in Transportation Facilities," edited by G.C. Lee and I.M. Friedland, 8/29/97, (PB98-128911, A25, MR-A04).

NCEER-97-0006 "Cumulative Seismic Damage of Reinforced Concrete Bridge Piers," by S.K. Kunnath, A. El-Bahy, A. Taylor and W. Stone, 9/2/97, (PB98-108814, A11, MF-A03).

NCEER-97-0007 "Structural Details to Accommodate Seismic Movements of Highway Bridges and Retaining Walls," by R.A. Imbsen, R.A. Schamber, E. Thorkildsen, A. Kartoum, B.T. Martin, T.N. Rosser and J.M. Kulicki, 9/3/97, (PB98-108996, A09, MF-A02).

NCEER-97-0008 "A Method for Earthquake Motion-Damage Relationships with Application to Reinforced Concrete Frames," by A. Singhal and A.S. Kiremidjian, 9/10/97, (PB98-108988, A13, MF-A03).

NCEER-97-0009 "Seismic Analysis and Design of Bridge Abutments Considering Sliding and Rotation," by K. Fishman and R. Richards, Jr., 9/15/97, (PB98-108897, A06, MF-A02).

NCEER-97-0010 "Proceedings of the FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities," edited by I.M. Friedland, M.S. Power and R.L. Mayes, 9/22/97, (PB98-128903, A21, MF-A04).

NCEER-97-0011 "Seismic Analysis for Design or Retrofit of Gravity Bridge Abutments," by K.L. Fishman, R. Richards, Jr. and R.C. Divito, 10/2/97, (PB98-128937, A08, MF-A02).

NCEER-97-0012 "Evaluation of Simplified Methods of Analysis for Yielding Structures," by P. Tsopelas, M.C. Constantinou, C.A. Kircher and A.S. Whittaker, 10/31/97, (PB98-128929, A10, MF-A03).

NCEER-97-0013 "Seismic Design of Bridge Columns Based on Control and Repairability of Damage," by C-T. Cheng and J.B. Mander, 12/8/97, (PB98-144249, A11, MF-A03).

NCEER-97-0014 "Seismic Resistance of Bridge Piers Based on Damage Avoidance Design," by J.B. Mander and C-T. Cheng, 12/10/97, (PB98-144223, A09, MF-A02).

NCEER-97-0015 “Seismic Response of Nominally Symmetric Systems with Strength Uncertainty,” by S. Balopoulou and M. Grigoriu, 12/23/97, (PB98-153422, A11, MF-A03).

NCEER-97-0016 “Evaluation of Seismic Retrofit Methods for Reinforced Concrete Bridge Columns,” by T.J. Wipf, F.W. Klaiber and F.M. Russo, 12/28/97, (PB98-144215, A12, MF-A03).

NCEER-97-0017 “Seismic Fragility of Existing Conventional Reinforced Concrete Highway Bridges,” by C.L. Mullen and A.S. Cakmak, 12/30/97, (PB98-153406, A08, MF-A02).

NCEER-97-0018 “Loss Asssessment of Memphis Buildings,” edited by D.P. Abrams and M. Shinozuka, 12/31/97, (PB98-144231, A13, MF-A03).

NCEER-97-0019 “Seismic Evaluation of Frames with Infill Walls Using Quasi-static Experiments,” by K.M. Mosalam, R.N. White and P. Gergely, 12/31/97, (PB98-153455, A07, MF-A02).

NCEER-97-0020 “Seismic Evaluation of Frames with Infill Walls Using Pseudo-dynamic Experiments,” by K.M. Mosalam, R.N. White and P. Gergely, 12/31/97, (PB98-153430, A07, MF-A02).

NCEER-97-0021 “Computational Strategies for Frames with Infill Walls: Discrete and Smeared Crack Analyses and Seismic Fragility,” by K.M. Mosalam, R.N. White and P. Gergely, 12/31/97, (PB98-153414, A10, MF-A02).

NCEER-97-0022 "Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils," edited by T.L. Youd and I.M. Idriss, 12/31/97, (PB98-155617, A15, MF-A03).

MCEER-98-0001 "Extraction of Nonlinear Hysteretic Properties of Seismically Isolated Bridges from Quick-Release Field Tests," by Q. Chen, B.M. Douglas, E.M. Maragakis and I.G. Buckle, 5/26/98, (PB99-118838, A06, MF-A01).

MCEER-98-0002 "Methodologies for Evaluating the Importance of Highway Bridges," by A. Thomas, S. Eshenaur and J. Kulicki, 5/29/98, (PB99-118846, A10, MF-A02).

MCEER-98-0003 "Capacity Design of Bridge Piers and the Analysis of Overstrength," by J.B. Mander, A. Dutta and P. Goel, 6/1/98, (PB99-118853, A09, MF-A02).

MCEER-98-0004 "Evaluation of Bridge Damage Data from the Loma Prieta and Northridge, California Earthquakes," by N. Basoz and A. Kiremidjian, 6/2/98, (PB99-118861, A15, MF-A03).

MCEER-98-0005 "Screening Guide for Rapid Assessment of Liquefaction Hazard at Highway Bridge Sites," by T. L. Youd, 6/16/98, (PB99-118879, A06, not available on microfiche).

MCEER-98-0006 "Structural Steel and Steel/Concrete Interface Details for Bridges," by P. Ritchie, N. Kauhl and J. Kulicki, 7/13/98, (PB99-118945, A06, MF-A01).

MCEER-98-0007 "Capacity Design and Fatigue Analysis of Confined Concrete Columns," by A. Dutta and J.B. Mander, 7/14/98, (PB99-118960, A14, MF-A03).

MCEER-98-0008 "Proceedings of the Workshop on Performance Criteria for Telecommunication Services Under Earthquake Conditions," edited by A.J. Schiff, 7/15/98, (PB99-118952, A08, MF-A02).

MCEER-98-0009 "Fatigue Analysis of Unconfined Concrete Columns," by J.B. Mander, A. Dutta and J.H. Kim, 9/12/98, (PB99-123655, A10, MF-A02).

MCEER-98-0010 "Centrifuge Modeling of Cyclic Lateral Response of Pile-Cap Systems and Seat-Type Abutments in Dry Sands," by A.D. Gadre and R. Dobry, 10/2/98, (PB99-123606, A13, MF-A03).

MCEER-98-0011 "IDARC-BRIDGE: A Computational Platform for Seismic Damage Assessment of Bridge Structures," by A.M. Reinhorn, V. Simeonov, G. Mylonakis and Y. Reichman, 10/2/98, (PB99-162919, A15, MF-A03).

MCEER-98-0012 "Experimental Investigation of the Dynamic Response of Two Bridges Before and After Retrofitting with Elastomeric Bearings," by D.A. Wendichansky, S.S. Chen and J.B. Mander, 10/2/98, (PB99-162927, A15, MF-A03).

MCEER-98-0013 "Design Procedures for Hinge Restrainers and Hinge Sear Width for Multiple-Frame Bridges," by R. Des Roches and G.L. Fenves, 11/3/98, (PB99-140477, A13, MF-A03).

MCEER-98-0014 "Response Modification Factors for Seismically Isolated Bridges," by M.C. Constantinou and J.K. Quarshie, 11/3/98, (PB99-140485, A14, MF-A03).

MCEER-98-0015 "Proceedings of the U.S.-Italy Workshop on Seismic Protective Systems for Bridges," edited by I.M. Friedland and M.C. Constantinou, 11/3/98, (PB2000-101711, A22, MF-A04).

MCEER-98-0016 "Appropriate Seismic Reliability for Critical Equipment Systems: Recommendations Based on Regional Analysis of Financial and Life Loss," by K. Porter, C. Scawthorn, C. Taylor and N. Blais, 11/10/98, (PB99-157265, A08, MF-A02).

MCEER-98-0017 "Proceedings of the U.S. Japan Joint Seminar on Civil Infrastructure Systems Research," edited by M. Shinozuka and A. Rose, 11/12/98, (PB99-156713, A16, MF-A03).

MCEER-98-0018 "Modeling of Pile Footings and Drilled Shafts for Seismic Design," by I. PoLam, M. Kapuskar and D. Chaudhuri, 12/21/98, (PB99-157257, A09, MF-A02).

MCEER-99-0001 "Seismic Evaluation of a Masonry Infilled Reinforced Concrete Frame by Pseudodynamic Testing," by S.G. Buonopane and R.N. White, 2/16/99, (PB99-162851, A09, MF-A02).

MCEER-99-0002 "Response History Analysis of Structures with Seismic Isolation and Energy Dissipation Systems: Verification Examples for Program SAP2000," by J. Scheller and M.C. Constantinou, 2/22/99, (PB99-162869, A08, MF-A02).

MCEER-99-0003 "Experimental Study on the Seismic Design and Retrofit of Bridge Columns Including Axial Load Effects," by A. Dutta, T. Kokorina and J.B. Mander, 2/22/99, (PB99-162877, A09, MF-A02).

MCEER-99-0004 "Experimental Study of Bridge Elastomeric and Other Isolation and Energy Dissipation Systems with Emphasis on Uplift Prevention and High Velocity Near-source Seismic Excitation," by A. Kasalanati and M. C. Constantinou, 2/26/99, (PB99-162885, A12, MF-A03).

MCEER-99-0005 "Truss Modeling of Reinforced Concrete Shear-flexure Behavior," by J.H. Kim and J.B. Mander, 3/8/99, (PB99-163693, A12, MF-A03).

MCEER-99-0006 "Experimental Investigation and Computational Modeling of Seismic Response of a 1:4 Scale Model Steel Structure with a Load Balancing Supplemental Damping System," by G. Pekcan, J.B. Mander and S.S. Chen, 4/2/99, (PB99-162893, A11, MF-A03).

MCEER-99-0007 "Effect of Vertical Ground Motions on the Structural Response of Highway Bridges," by M.R. Button, C.J. Cronin and R.L. Mayes, 4/10/99, (PB2000-101411, A10, MF-A03).

MCEER-99-0008 "Seismic Reliability Assessment of Critical Facilities: A Handbook, Supporting Documentation, and Model Code Provisions," by G.S. Johnson, R.E. Sheppard, M.D. Quilici, S.J. Eder and C.R. Scawthorn, 4/12/99, (PB2000-101701, A18, MF-A04).

MCEER-99-0009 "Impact Assessment of Selected MCEER Highway Project Research on the Seismic Design of Highway Structures," by C. Rojahn, R. Mayes, D.G. Anderson, J.H. Clark, D'Appolonia Engineering, S. Gloyd and R.V. Nutt, 4/14/99, (PB99-162901, A10, MF-A02).

MCEER-99-0010 "Site Factors and Site Categories in Seismic Codes," by R. Dobry, R. Ramos and M.S. Power, 7/19/99, (PB2000-101705, A08, MF-A02).

MCEER-99-0011 "Restrainer Design Procedures for Multi-Span Simply-Supported Bridges," by M.J. Randall, M. Saiidi, E. Maragakis and T. Isakovic, 7/20/99, (PB2000-101702, A10, MF-A02).

MCEER-99-0012 "Property Modification Factors for Seismic Isolation Bearings," by M.C. Constantinou, P. Tsopelas, A. Kasalanati and E. Wolff, 7/20/99, (PB2000-103387, A11, MF-A03).

MCEER-99-0013 "Critical Seismic Issues for Existing Steel Bridges," by P. Ritchie, N. Kauhl and J. Kulicki, 7/20/99, (PB2000-101697, A09, MF-A02).

MCEER-99-0014 "Nonstructural Damage Database," by A. Kao, T.T. Soong and A. Vender, 7/24/99, (PB2000-101407, A06, MF-A01).

MCEER-99-0015 "Guide to Remedial Measures for Liquefaction Mitigation at Existing Highway Bridge Sites," by H.G. Cooke and J. K. Mitchell, 7/26/99, (PB2000-101703, A11, MF-A03).

MCEER-99-0016 "Proceedings of the MCEER Workshop on Ground Motion Methodologies for the Eastern United States," edited by N. Abrahamson and A. Becker, 8/11/99, (PB2000-103385, A07, MF-A02).

MCEER-99-0017 "Quindío, Colombia Earthquake of January 25, 1999: Reconnaissance Report," by A.P. Asfura and P.J. Flores, 10/4/99, (PB2000-106893, A06, MF-A01).

MCEER-99-0018 "Hysteretic Models for Cyclic Behavior of Deteriorating Inelastic Structures," by M.V. Sivaselvan and A.M. Reinhorn, 11/5/99, (PB2000-103386, A08, MF-A02).

MCEER-99-0019 "Proceedings of the 7th U.S.- Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction," edited by T.D. O'Rourke, J.P. Bardet and M. Hamada, 11/19/99, (PB2000-103354, A99, MF-A06).

MCEER-99-0020 "Development of Measurement Capability for Micro-Vibration Evaluations with Application to Chip Fabrication Facilities," by G.C. Lee, Z. Liang, J.W. Song, J.D. Shen and W.C. Liu, 12/1/99, (PB2000-105993, A08, MF-A02).

MCEER-99-0021 "Design and Retrofit Methodology for Building Structures with Supplemental Energy Dissipating Systems," by G. Pekcan, J.B. Mander and S.S. Chen, 12/31/99, (PB2000-105994, A11, MF-A03).

MCEER-00-0001 "The Marmara, Turkey Earthquake of August 17, 1999: Reconnaissance Report," edited by C. Scawthorn; with major contributions by M. Bruneau, R. Eguchi, T. Holzer, G. Johnson, J. Mander, J. Mitchell, W. Mitchell, A. Papageorgiou, C. Scaethorn, and G. Webb, 3/23/00, (PB2000-106200, A11, MF-A03).

MCEER-00-0002 "Proceedings of the MCEER Workshop for Seismic Hazard Mitigation of Health Care Facilities," edited by G.C. Lee, M. Ettouney, M. Grigoriu, J. Hauer and J. Nigg, 3/29/00, (PB2000-106892, A08, MF-A02).

MCEER-00-0003 "The Chi-Chi, Taiwan Earthquake of September 21, 1999: Reconnaissance Report," edited by G.C. Lee and C.H. Loh, with major contributions by G.C. Lee, M. Bruneau, I.G. Buckle, S.E. Chang, P.J. Flores, T.D. O'Rourke, M. Shinozuka, T.T. Soong, C-H. Loh, K-C. Chang, Z-J. Chen, J-S. Hwang, M-L. Lin, G-Y. Liu, K-C. Tsai, G.C. Yao and C-L. Yen, 4/30/00, (PB2001-100980, A10, MF-A02).

MCEER-00-0004 "Seismic Retrofit of End-Sway Frames of Steel Deck-Truss Bridges with a Supplemental Tendon System: Experimental and Analytical Investigation," by G. Pekcan, J.B. Mander and S.S. Chen, 7/1/00, (PB2001-100982, A10, MF-A02).

MCEER-00-0005 "Sliding Fragility of Unrestrained Equipment in Critical Facilities," by W.H. Chong and T.T. Soong, 7/5/00, (PB2001-100983, A08, MF-A02).

MCEER-00-0006 "Seismic Response of Reinforced Concrete Bridge Pier Walls in the Weak Direction," by N. Abo-Shadi, M. Saiidi and D. Sanders, 7/17/00, (PB2001-100981, A17, MF-A03).

MCEER-00-0007 "Low-Cycle Fatigue Behavior of Longitudinal Reinforcement in Reinforced Concrete Bridge Columns," by J. Brown and S.K. Kunnath, 7/23/00, (PB2001-104392, A08, MF-A02).

MCEER-00-0008 "Soil Structure Interaction of Bridges for Seismic Analysis," I. PoLam and H. Law, 9/25/00, (PB2001-105397, A08, MF-A02).

MCEER-00-0009 "Proceedings of the First MCEER Workshop on Mitigation of Earthquake Disaster by Advanced Technologies (MEDAT-1), edited by M. Shinozuka, D.J. Inman and T.D. O'Rourke, 11/10/00, (PB2001-105399, A14, MF-A03).

MCEER-00-0010 "Development and Evaluation of Simplified Procedures for Analysis and Design of Buildings with Passive Energy Dissipation Systems, Revision 01," by O.M. Ramirez, M.C. Constantinou, C.A. Kircher, A.S. Whittaker, M.W. Johnson, J.D. Gomez and C. Chrysostomou, 11/16/01, (PB2001-105523, A23, MF-A04).

MCEER-00-0011 "Dynamic Soil-Foundation-Structure Interaction Analyses of Large Caissons," by C-Y. Chang, C-M. Mok, Z-L. Wang, R. Settgast, F. Waggoner, M.A. Ketchum, H.M. Gonnermann and C-C. Chin, 12/30/00, (PB2001-104373, A07, MF-A02).

MCEER-00-0012 "Experimental Evaluation of Seismic Performance of Bridge Restrainers," by A.G. Vlassis, E.M. Maragakis and M. Saiid Saiidi, 12/30/00, (PB2001-104354, A09, MF-A02).

MCEER-00-0013 "Effect of Spatial Variation of Ground Motion on Highway Structures," by M. Shinozuka, V. Saxena and G. Deodatis, 12/31/00, (PB2001-108755, A13, MF-A03).

MCEER-00-0014 "A Risk-Based Methodology for Assessing the Seismic Performance of Highway Systems," by S.D. Werner, C.E. Taylor, J.E. Moore, II, J.S. Walton and S. Cho, 12/31/00, (PB2001-108756, A14, MF-A03).

MCEER-01-0001 "Experimental Investigation of P-Delta Effects to Collapse During Earthquakes," by D. Vian and M. Bruneau, 6/25/01, (PB2002-100534, A17, MF-A03).

MCEER-01-0002 "Proceedings of the Second MCEER Workshop on Mitigation of Earthquake Disaster by Advanced Technologies (MEDAT-2)," edited by M. Bruneau and D.J. Inman, 7/23/01, (PB2002-100434, A16, MF-A03).

MCEER-01-0003 "Sensitivity Analysis of Dynamic Systems Subjected to Seismic Loads," by C. Roth and M. Grigoriu, 9/18/01, (PB2003-100884, A12, MF-A03).

MCEER-01-0004 "Overcoming Obstacles to Implementing Earthquake Hazard Mitigation Policies: Stage 1 Report," by D.J. Alesch and W.J. Petak, 12/17/01, (PB2002-107949, A07, MF-A02).

MCEER-01-0005 "Updating Real-Time Earthquake Loss Estimates: Methods, Problems and Insights," by C.E. Taylor, S.E. Chang and R.T. Eguchi, 12/17/01, (PB2002-107948, A05, MF-A01).

MCEER-01-0006 "Experimental Investigation and Retrofit of Steel Pile Foundations and Pile Bents Under Cyclic Lateral Loadings," by A. Shama, J. Mander, B. Blabac and S. Chen, 12/31/01, (PB2002-107950, A13, MF-A03).

MCEER-02-0001 "Assessment of Performance of Bolu Viaduct in the 1999 Duzce Earthquake in Turkey" by P.C. Roussis, M.C. Constantinou, M. Erdik, E. Durukal and M. Dicleli, 5/8/02, (PB2003-100883, A08, MF-A02).

MCEER-02-0002 "Seismic Behavior of Rail Counterweight Systems of Elevators in Buildings," by M.P. Singh, Rildova and L.E. Suarez, 5/27/02. (PB2003-100882, A11, MF-A03).

MCEER-02-0003 "Development of Analysis and Design Procedures for Spread Footings," by G. Mylonakis, G. Gazetas, S. Nikolaou and A. Chauncey, 10/02/02, (PB2004-101636, A13, MF-A03, CD-A13).

MCEER-02-0004 "Bare-Earth Algorithms for Use with SAR and LIDAR Digital Elevation Models," by C.K. Huyck, R.T. Eguchi and B. Houshmand, 10/16/02, (PB2004-101637, A07, CD-A07).

MCEER-02-0005 "Review of Energy Dissipation of Compression Members in Concentrically Braced Frames," by K.Lee and M. Bruneau, 10/18/02, (PB2004-101638, A10, CD-A10).

MCEER-03-0001 "Experimental Investigation of Light-Gauge Steel Plate Shear Walls for the Seismic Retrofit of Buildings" by J. Berman and M. Bruneau, 5/2/03, (PB2004-101622, A10, MF-A03, CD-A10).

MCEER-03-0002 "Statistical Analysis of Fragility Curves," by M. Shinozuka, M.Q. Feng, H. Kim, T. Uzawa and T. Ueda, 6/16/03, (PB2004-101849, A09, CD-A09).

MCEER-03-0003 "Proceedings of the Eighth U.S.-Japan Workshop on Earthquake Resistant Design f Lifeline Facilities and Countermeasures Against Liquefaction," edited by M. Hamada, J.P. Bardet and T.D. O'Rourke, 6/30/03, (PB2004-104386, A99, CD-A99).

MCEER-03-0004 "Proceedings of the PRC-US Workshop on Seismic Analysis and Design of Special Bridges," edited by L.C. Fan and G.C. Lee, 7/15/03, (PB2004-104387, A14, CD-A14).

MCEER-03-0005 "Urban Disaster Recovery: A Framework and Simulation Model," by S.B. Miles and S.E. Chang, 7/25/03, (PB2004-104388, A07, CD-A07).

MCEER-03-0006 "Behavior of Underground Piping Joints Due to Static and Dynamic Loading," by R.D. Meis, M. Maragakis and R. Siddharthan, 11/17/03, (PB2005-102194, A13, MF-A03, CD-A00).

MCEER-03-0007 "Seismic Vulnerability of Timber Bridges and Timber Substructures," by A.A. Shama, J.B. Mander, I.M. Friedland and D.R. Allicock, 12/15/03.

MCEER-04-0001 "Experimental Study of Seismic Isolation Systems with Emphasis on Secondary System Response and Verification of Accuracy of Dynamic Response History Analysis Methods," by E. Wolff and M. Constantinou, 1/16/04 (PB2005-102195, A99, MF-E08, CD-A00).

MCEER-04-0002 "Tension, Compression and Cyclic Testing of Engineered Cementitious Composite Materials," by K. Kesner and S.L. Billington, 3/1/04, (PB2005-102196, A08, CD-A08).

MCEER-04-0003 "Cyclic Testing of Braces Laterally Restrained by Steel Studs to Enhance Performance During Earthquakes," by O.C. Celik, J.W. Berman and M. Bruneau, 3/16/04, (PB2005-102197, A13, MF-A03, CD-A00).

MCEER-04-0004 "Methodologies for Post Earthquake Building Damage Detection Using SAR and Optical Remote Sensing: Application to the August 17, 1999 Marmara, Turkey Earthquake," by C.K. Huyck, B.J. Adams, S. Cho, R.T. Eguchi, B. Mansouri and B. Houshmand, 6/15/04, (PB2005-104888, A10, CD-A00).

MCEER-04-0005 "Nonlinear Structural Analysis Towards Collapse Simulation: A Dynamical Systems Approach," by M.V. Sivaselvan and A.M. Reinhorn, 6/16/04, (PB2005-104889, A11, MF-A03, CD-A00).

MCEER-04-0006 "Proceedings of the Second PRC-US Workshop on Seismic Analysis and Design of Special Bridges," edited by G.C. Lee and L.C. Fan, 6/25/04, (PB2005-104890, A16, CD-A00).

MCEER-04-0007 "Seismic Vulnerability Evaluation of Axially Loaded Steel Built-up Laced Members," by K. Lee and M. Bruneau, 6/30/04, (PB2005-104891, A16, CD-A00).

MCEER-04-0008 "Evaluation of Accuracy of Simplified Methods of Analysis and Design of Buildings with Damping Systems for Near-Fault and for Soft-Soil Seismic Motions," by E.A. Pavlou and M.C. Constantinou, 8/16/04, (PB2005-104892, A08, MF-A02, CD-A00).

MCEER-04-0009 "Assessment of Geotechnical Issues in Acute Care Facilities in California," by M. Lew, T.D. O'Rourke, R. Dobry and M. Koch, 9/15/04, (PB2005-104893, A08, CD-A00).

MCEER-04-0010 "Scissor-Jack-Damper Energy Dissipation System," by A.N. Sigaher-Boyle and M.C. Constantinou, 12/1/04 (PB2005-108221).

MCEER-04-0011 "Seismic Retrofit of Bridge Steel Truss Piers Using a Controlled Rocking Approach," by M. Pollino and M. Bruneau, 12/20/04 (PB2006-105795).

MCEER-05-0001 "Experimental and Analytical Studies of Structures Seismically Isolated with an Uplift-Restraint Isolation System," by P.C. Roussis and M.C. Constantinou, 1/10/05 (PB2005-108222).

MCEER-05-0002 "A Versatile Experimentation Model for Study of Structures Near Collapse Applied to Seismic Evaluation of Irregular Structures," by D. Kusumastuti, A.M. Reinhorn and A. Rutenberg, 3/31/05 (PB2006-101523).

MCEER-05-0003 "Proceedings of the Third PRC-US Workshop on Seismic Analysis and Design of Special Bridges," edited by L.C. Fan and G.C. Lee, 4/20/05, (PB2006-105796).

MCEER-05-0004 "Approaches for the Seismic Retrofit of Braced Steel Bridge Piers and Proof-of-Concept Testing of an Eccentrically Braced Frame with Tubular Link," by J.W. Berman and M. Bruneau, 4/21/05 (PB2006-101524).

MCEER-05-0005 "Simulation of Strong Ground Motions for Seismic Fragility Evaluation of Nonstructural Components in Hospitals," by A. Wanitkorkul and A. Filiatrault, 5/26/05 (PB2006-500027).

MCEER-05-0006 "Seismic Safety in California Hospitals: Assessing an Attempt to Accelerate the Replacement or Seismic Retrofit of Older Hospital Facilities," by D.J. Alesch, L.A. Arendt and W.J. Petak, 6/6/05 (PB2006-105794).

MCEER-05-0007 "Development of Seismic Strengthening and Retrofit Strategies for Critical Facilities Using Engineered Cementitious Composite Materials," by K. Kesner and S.L. Billington, 8/29/05 (PB2006-111701).

MCEER-05-0008 "Experimental and Analytical Studies of Base Isolation Systems for Seismic Protection of Power Transformers," by N. Murota, M.Q. Feng and G-Y. Liu, 9/30/05 (PB2006-111702).

MCEER-05-0009 "3D-BASIS-ME-MB: Computer Program for Nonlinear Dynamic Analysis of Seismically Isolated Structures," by P.C. Tsopelas, P.C. Roussis, M.C. Constantinou, R. Buchanan and A.M. Reinhorn, 10/3/05 (PB2006-111703).

MCEER-05-0010 "Steel Plate Shear Walls for Seismic Design and Retrofit of Building Structures," by D. Vian and M. Bruneau, 12/15/05 (PB2006-111704).

MCEER-05-0011 "The Performance-Based Design Paradigm," by M.J. Astrella and A. Whittaker, 12/15/05 (PB2006-111705).

MCEER-06-0001 "Seismic Fragility of Suspended Ceiling Systems," H. Badillo-Almaraz, A.S. Whittaker, A.M. Reinhorn and G.P. Cimellaro, 2/4/06 (PB2006-111706).

MCEER-06-0002 "Multi-Dimensional Fragility of Structures," by G.P. Cimellaro, A.M. Reinhorn and M. Bruneau, 3/1/06 (PB2007-106974, A09, MF-A02, CD A00).

MCEER-06-0003 "Built-Up Shear Links as Energy Dissipators for Seismic Protection of Bridges," by P. Dusicka, A.M. Itani and I.G. Buckle, 3/15/06 (PB2006-111708).

MCEER-06-0004 "Analytical Investigation of the Structural Fuse Concept," by R.E. Vargas and M. Bruneau, 3/16/06 (PB2006-111709).

MCEER-06-0005 "Experimental Investigation of the Structural Fuse Concept," by R.E. Vargas and M. Bruneau, 3/17/06 (PB2006-111710).

MCEER-06-0006 "Further Development of Tubular Eccentrically Braced Frame Links for the Seismic Retrofit of Braced Steel Truss Bridge Piers," by J.W. Berman and M. Bruneau, 3/27/06 (PB2007-105147).

MCEER-06-0007 "REDARS Validation Report," by S. Cho, C.K. Huyck, S. Ghosh and R.T. Eguchi, 8/8/06 (PB2007-106983).

MCEER-06-0008 "Review of Current NDE Technologies for Post-Earthquake Assessment of Retrofitted Bridge Columns," by J.W. Song, Z. Liang and G.C. Lee, 8/21/06 06 (PB2007-106984).

MCEER-06-0009 "Liquefaction Remediation in Silty Soils Using Dynamic Compaction and Stone Columns," by S. Thevanayagam, G.R. Martin, R. Nashed, T. Shenthan, T. Kanagalingam and N. Ecemis, 8/28/06 06 (PB2007-106985).

MCEER-06-0010 "Conceptual Design and Experimental Investigation of Polymer Matrix Composite Infill Panels for Seismic Retrofitting," by W. Jung, M. Chiewanichakorn and A.J. Aref, 9/21/06 (PB2007-106986).

MCEER-06-0011 "A Study of the Coupled Horizontal-Vertical Behavior of Elastomeric and Lead-Rubber Seismic Isolation Bearings," by G.P. Warn and A.S. Whittaker, 9/22/06 (PB2007-108679).

MCEER-06-0012 "Proceedings of the Fourth PRC-US Workshop on Seismic Analysis and Design of Special Bridges: Advancing Bridge Technologies in Research, Design, Construction and Preservation," Edited by L.C. Fan, G.C. Lee and L. Ziang, 10/12/06 (PB2007-109042).

MCEER-06-0013 "Cyclic Response and Low Cycle Fatigue Characteristics of Plate Steels," by P. Dusicka, A.M. Itani and I.G. Buckle, 11/1/06 06 (PB2007-106987).

MCEER-06-0014 "Proceedings of the Second US-Taiwan Bridge Engineering Workshop," edited by W.P. Yen, J. Shen, J-Y. Chen and M. Wang, 11/15/06.

MCEER-06-0015 "User Manual and Technical Documentation for the REDARS™ Import Wizard," by S. Cho, S. Ghosh, C.K. Huyck and S.D. Werner, 11/30/06 (PB2007-114766).

MCEER-06-0016 "Hazard Mitigation Strategy and Monitoring Technologies for Urban and Infrastructure Public Buildings: Proceedings of the China-US Workshops," edited by X.Y. Zhou, A.L. Zhang, G.C. Lee and M. Tong, 12/12/06 (PB2008-500018).

MCEER-07-0001 "Static and Kinetic Coefficients of Friction for Rigid Blocks," by C. Kafali, S. Fathali, M. Grigoriu and A.S. Whittaker, 3/20/07 (PB2007-114767).

MCEER-07-0002 "Hazard Mitigation Investment Decision Making: Organizational Response to Legislative Mandate," by L.A. Arendt, D.J. Alesch and W.J. Petak, 4/9/07 (PB2007-114768).

MCEER-07-0003 “Seismic Behavior of Bidirectional-Resistant Ductile End Diaphragms with Unbonded Braces in Straight or Skewed Steel Bridges,” by O. Celik and M. Bruneau, 4/11/07 (PB2008-105141).

MCEER-07-0004 “Modeling Pile Behavior in Large Pile Groups Under Lateral Loading,” by A.M. Dodds and G.R. Martin, 4/16/07(PB2008-105142).

MCEER-07-0005 “Experimental Investigation of Blast Performance of Seismically Resistant Concrete-Filled Steel Tube Bridge Piers,” by S. Fujikura, M. Bruneau and D. Lopez-Garcia, 4/20/07 (PB2008-105143).

MCEER-07-0006 “Seismic Analysis of Conventional and Isolated Liquefied Natural Gas Tanks Using Mechanical Analogs,” by I.P. Christovasilis and A.S. Whittaker, 5/1/07.

MCEER-07-0007 “Experimental Seismic Performance Evaluation of Isolation/Restraint Systems for Mechanical Equipment – Part 1: Heavy Equipment Study,” by S. Fathali and A. Filiatrault, 6/6/07 (PB2008-105144).

MCEER-07-0008 “Seismic Vulnerability of Timber Bridges and Timber Substructures,” by A.A. Sharma, J.B. Mander, I.M. Friedland and D.R. Allicock, 6/7/07 (PB2008-105145).

MCEER-07-0009 “Experimental and Analytical Study of the XY-Friction Pendulum (XY-FP) Bearing for Bridge Applications,” by C.C. Marin-Artieda, A.S. Whittaker and M.C. Constantinou, 6/7/07 (PB2008-105191).

MCEER-07-0010 “Proceedings of the PRC-US Earthquake Engineering Forum for Young Researchers,” Edited by G.C. Lee and X.Z. Qi, 6/8/07.

MCEER-07-0011 “Design Recommendations for Perforated Steel Plate Shear Walls,” by R. Purba and M. Bruneau, 6/18/07, (PB2008-105192).

MCEER-07-0012 “Performance of Seismic Isolation Hardware Under Service and Seismic Loading,” by M.C. Constantinou, A.S. Whittaker, Y. Kalpakidis, D.M. Fenz and G.P. Warn, 8/27/07, (PB2008-105193).

MCEER-07-0013 “Experimental Evaluation of the Seismic Performance of Hospital Piping Subassemblies,” by E.R. Goodwin, E. Maragakis and A.M. Itani, 9/4/07, (PB2008-105194).

MCEER-07-0014 “A Simulation Model of Urban Disaster Recovery and Resilience: Implementation for the 1994 Northridge Earthquake,” by S. Miles and S.E. Chang, 9/7/07, (PB2008-106426).

MCEER-07-0015 “Statistical and Mechanistic Fragility Analysis of Concrete Bridges,” by M. Shinozuka, S. Banerjee and S-H. Kim, 9/10/07, (PB2008-106427).

MCEER-07-0016 “Three-Dimensional Modeling of Inelastic Buckling in Frame Structures,” by M. Schachter and AM. Reinhorn, 9/13/07, (PB2008-108125).

MCEER-07-0017 “Modeling of Seismic Wave Scattering on Pile Groups and Caissons,” by I. Po Lam, H. Law and C.T. Yang, 9/17/07.

MCEER-07-0018 “Bridge Foundations: Modeling Large Pile Groups and Caissons for Seismic Design,” by I. Po Lam, H. Law and G.R. Martin (Coordinating Author), 12/1/07.

MCEER-07-0019 “Principles and Performance of Roller Seismic Isolation Bearings for Highway Bridges,” by G.C. Lee, Y.C. Ou, Z. Liang, T.C. Niu and J. Song, 12/10/07.

MCEER-07-0020 “Centrifuge Modeling of Permeability and Pinning Reinforcement Effects on Pile Response to Lateral Spreading,” by L.L Gonzalez-Lagos, T. Abdoun and R. Dobry, 12/10/07.

MCEER-07-0021 “Damage to the Highway System from the Pisco, Perú Earthquake of August 15, 2007,” by J.S. O’Connor, L. Mesa and M. Nykamp, 12/10/07, (PB2008-108126).

MCEER-07-0022 “Experimental Seismic Performance Evaluation of Isolation/Restraint Systems for Mechanical Equipment – Part 2: Light Equipment Study,” by S. Fathali and A. Filiatrault, 12/13/07.

MCEER-07-0023 "Fragility Considerations in Highway Bridge Design," by M. Shinozuka, S. Banerjee and S.H. Kim, 12/14/07.

MCEER-07-0024 "Performance Estimates for Seismically Isolated Bridges," by G.P. Warn and A.S. Whittaker, 12/30/07.

MCEER-08-0001 "Seismic Performance of Steel Girder Bridge Superstructures with Conventional Cross Frames," by L.P. Carden, A.M. Itani and I.G. Buckle, 1/7/08.

MCEER-08-0002 "Seismic Performance of Steel Girder Bridge Superstructures with Ductile End Cross Frames with Seismic Isolators," by L.P. Carden, A.M. Itani and I.G. Buckle, 1/7/08.

MCEER-08-0003 "Analytical and Experimental Investigation of a Controlled Rocking Approach for Seismic Protection of Bridge Steel Truss Piers," by M. Pollino and M. Bruneau, 1/21/08.

MCEER-08-0004 "Linking Lifeline Infrastructure Performance and Community Disaster Resilience: Models and Multi-Stakeholder Processes," by S.E. Chang, C. Pasion, K. Tatebe and R. Ahmad, 3/3/08.

MCEER-08-0005 "Modal Analysis of Generally Damped Linear Structures Subjected to Seismic Excitations," by J. Song, Y-L. Chu, Z. Liang and G.C. Lee, 3/4/08.

MCEER-08-0006 "System Performance Under Multi-Hazard Environments," by C. Kafali and M. Grigoriu, 3/4/08.

MCEER-08-0007 "Mechanical Behavior of Multi-Spherical Sliding Bearings," by D.M. Fenz and M.C. Constantinou, 3/6/08.

MCEER-08-0008 "Post-Earthquake Restoration of the Los Angeles Water Supply System," by T.H.P. Tabucchi and R.A. Davidson, 3/7/08.

MCEER
EARTHQUAKE ENGINEERING TO EXTREME EVENTS
University at Buffalo, The State University of New York
Red Jacket Quadrangle ▪ Buffalo, New York 14261
Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
E-mail: *mceer@buffalo.edu* ▪ WWW Site *http://mceer.buffalo.edu*
University at Buffalo *The State University of New York*

ISSN 1520-295X