NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

State University of New York at Buffalo

SYSTEMS STUDY OF URBAN RESPONSE AND RECONSTRUCTION DUE TO CATASTROPHIC EARTHQUAKES

by

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Technical Report NCEER-88-0027

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NOTICE

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PREFACE

The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

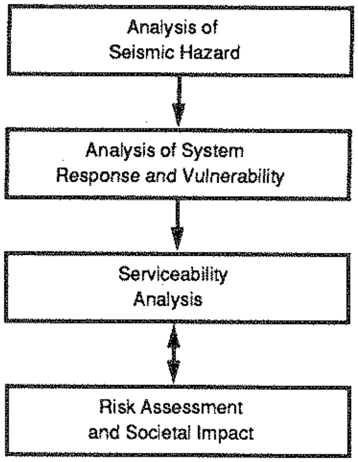
This technical report pertains to Program 3, Lifeline Systems, and more specifically to water delivery systems.

The safe and serviceable operation of lifeline systems such as gas, electricity, oil, water, communication and transportation networks, immediately after a severe earthquake, is of crucial importance to the welfare of the general public, and to the mitigation of seismic hazards upon society at large. The long-term goals of the lifeline study are to evaluate the seismic performance of lifeline systems in general, and to recommend measures for mitigating the societal risk arising from their failures.

From this point of view, Center researchers are concentrating on the study of specific existing lifeline systems, such as water delivery and crude oil transmission systems. The water delivery system study consists of two parts. The first studies the seismic performance of water delivery systems on the west coast, while the second addresses itself to the seismic performance of the water delivery system in Memphis, Tennessee. For both systems, post-earthquake fire fighting capabilities will be considered as a measure of seismic performance.

The components of the water delivery system study are shown in the accompanying figure.

Program Elements:



Tasks:

Wave Propagation, Fault Crossing
Liquefaction and Large Deformation
Above- and Under-ground Structure Interaction
Spatial Variability of Ground Motion

Soil-Structure Interaction, Pipe Response Analysis
Statistics of Repair/Damage
Post-Earthquake Data Gathering Procedure
Leakage Tests, Centrifuge Tests for Pipes

Post-Earthquake Firefighting Capability
System Reliability
Computer Code Development and Upgrading
Verification of Analytical Results

Mathematical Modeling
Socio-Economic Impact

Risk assessment and societal impact studies are an integral part of the lifeline systems program. Risk arising from lifeline system failures due to seismic action and its impact on society must be assessed. Measures for mitigating such an impact must be developed by engineers and scientists when they pertain to technical issues or by socio-economic experts when they relate to societal issues. In this way, the lifeline systems' response to a major earthquake, and the interactions among various subsystems can be better understood, thus providing knowledge that is useful in earthquake mitigation and preparedness planning. Some of these tasks are suitable for incorporation into expert systems for the management of lifelines in emergencies.

This technical report addresses itself to the issue of how lifeline systems damaged by earthquakes can be effectively restored under limited reconstruction resources. Such a restoration condition is an important component of the overall strategy for mitigating the societal impact of disasterous earthquakes.

ABSTRACT

The functioning of lifeline systems after a major earthquake is critical to the modern urban center. The system study of lifelines response to catastrophic earthquakes is the essential prerequisite step for the emergency management authority to form a mitigation and reconstruction plan in order to minimize the total loss caused by the earthquake.

This study develops an applied formulation of lifeline restoration processes in the post earthquake period by the method of Markov decision process. The objective of this research is to test various reconstruction strategies to determine optimal mitigation policies based upon various reconstruction goals, in particular, to optimize the distribution of limited reconstruction resources. By computer simulation, various scenarios are examined and useful information that is important to the emergency management authority is obtained.

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INTRODUCTION

1.1 Overview

Potentially catastrophic earthquakes occur often in many parts of the world. During the past 80 years, about 10 earthquakes with Richter magnitude 7.0 or larger occurred per year in the world. In each event, the casualties vary from hundreds to thousands and property damage can range from millions to billions of dollars. In the United States, 42 of the 50 states have experienced perceptible earthquake shaking in the past. During 1982, 70 earthquakes with Richter magnitude greater than 5.0 were recorded in the United States. On the average, by survey of historical statistics, a disastrous earthquake, one with Richter magnitude 8.0 or more, occurs in America once every twelve years.

Although southern California is regarded as a high risk seismic area in the United States, and New England is not generally considered as an area of seismic risk by the public, the likelihood of a major earthquake occurring in New England does exist. Based on statistics of historical data and geological observation, geologists unanimously agree on the inevitability of major earthquakes in California and New England, as well as the New York area, with Richter magnitude of 7.0 and larger. Because about 50% of the Nation's total population and resources are located around these likely earthquake zones, casualties could be high and property damage could total as much as $10 billion. Therefore, the U.S. has to treat this problem seriously.

Although a disastrous earthquake, generally speaking, is not controllable, adequate preparedness and proper response strategy to deal with such an event can dramatically reduce the casualties and property damage, according to the experience in the United States and other countries. Therefore, it is desirable to formulate and analyze the possible behaviors (states) of an urban system during and after a major earthquake, in order to devise preparedness and response plans for coping with potential disaster.

Past experience in major earthquakes shows us that much of the damage in a seismic event may be caused not only by the direct effect of earthquake shocks, but also by secondary events such as fire, gas explosion, toxic spill, interruption of transportation and communication, dam collapse and flooding. Fortunately, the secondary events are more controllable than the direct earthquake excitation. Although some suggestions were put forward to reduce the magnitude of a potential earthquake, such as releasing the energy of a potential earthquake gradually by some artificial method, no engineering method appears to be available in the near future. In contrast to the shock wave, the secondary events can be controlled, at least to some extent, if we fully understand the behavior of the system during and after a major earthquake.

Among all the factors influencing casualties and property damage, we are most interested in the behavior and dynamic response of lifeline systems in the urban areas subject to earthquake shocks. "Lifeline" is a general term denoting all networks and systems necessary for the sustenance of human life and well-being. It covers pipelines of all kinds, transportation networks, communication and power networks, health and hospital services, critical structures, etc. Because modern society is increasingly dependent on lifeline systems, especially in the urban center, the functioning of these systems in a post-earthquake environment is critical. Therefore, many aspects of earthquake and earthquake-caused damage to lifelines have been the subject of intensive research in recent years. While much work has been done to evaluate the dynamic response of lifelines to earthquakes, they have not been treated in general as a totally integrated urban system. For instance, mitigation polices for buildings and structures may influence the ability of an area's transportation and communication networks to remain functional. A holistic view of the situation, however, might provide insight into whether mitigation polices for strengthening structures, or provisions for establishing alternative emergency patterns of transportation and communication will prove most beneficial for reducing losses due to an earthquake. Additionally, the emergency management authority should have some priority list for the consideration of limited resources and the order of importance of subsystems when they develop a response plan.

Several factors make the evaluation of the dynamic response of lifelines to earthquakes very difficult. The dynamic response of a lifeline system to a major earthquake is a complicated process encompassing many variables such as earthquake magnitude and duration; population density and distribution characteristics; land-use patterns and construction techniques; geological configuration; vulnerability of other lifeline systems; complex response operations; and long-term physical, social and economic recovery policies.

1.2 Lifeline Earthquake Engineering

Lifeline earthquake engineering has been an intensive research field since the 1971 San Fernando earthquake. Considering that modern urban areas have been and are still growing day by day, and human activities are more dependent on lifeline systems than ever before, the understanding of the dynamic response of lifeline systems to a major earthquake becomes very important. Urban areas are very sensitive to the loss of service of lifelines under seismic hazard.

A brief review of past research work in the field will be helpful to establish the advances made in this study and identify actions which can now be taken to advance the current knowledge in the area. The past research work in the field can be classified in the following categories.

1.2.1 Discrete Event Simulation Method

The main objective of this approach is developing a methodology to evaluate lifeline system performance during large earthquakes in major metropolitan areas. The general approach to lifeline vulnerability analysis is through the integrated use of deterministic models, Monte Carlo methods and discrete event simulation on digital computer.

Schiff [9] chose an electric transmission system in an urban center as a case study. The simulation began with the choice of a particular hypothesized earthquake. The severity of ground motion is found at each site where lifeline facilities are located, and damage degree of equipment at each site is determined by some attenuation law - the relationship between damage probability of system and earthquake intensity. The local seismic environment is also used to estimate the reduction in power demand, due to damage, by customers. Post-earthquake recovery operations are simulated day-by-day until full recovery is achieved under emergency operation conditions. Results of the simulation include identification of which equipment had to be repaired, man-hours and other resources required, and customers' service statistics for each day. Several experiments assessed the basic seismic response of the system and affects of random variation in equipment damages, repair times and travel times. Sensitivity analysis was performed, examining variations in post-earthquake demand reduction, spare transformer availability, loss of generality capacity, increased seismic resistance of certain equipment and priorities for assigning repair crews.

The logical structure of the power system simulation is shown in Fig. 1-1 [9].

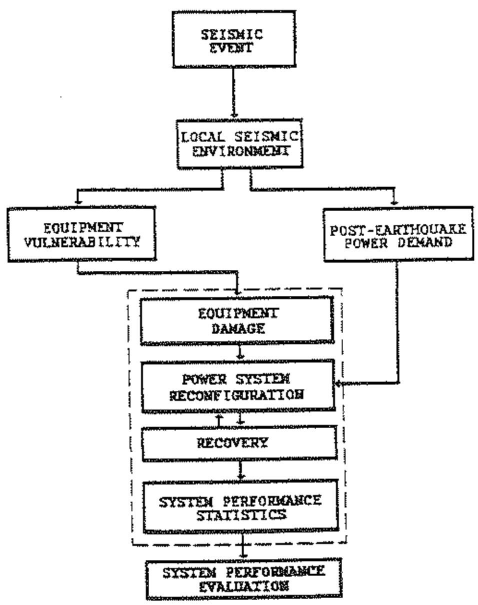

Figure 1-1 Logical Structure of Power System Simulation

1.2.2 Failure Probability Analysis

In the probability and network analysis method [8], the researchers are mainly interested in finding the failure probability of lifeline systems under a given earthquake. In the analysis, the lifeline system is treated as a network consisting of nodes (sources, distribution center, pumping stations, etc.) and links (transportation or communication lines, roads and pipelines, etc.). In contrast to buildings and structures, lifeline networks are usually continuously distributed over a sizable geographic area. Therefore, the various parts of the system will undergo different levels of shock due to any given earthquake. This fact suggests that a different approach from that of the case of buildings and structures should be used. One such approach is finding the probability of the network failure. However, the term "failure" might mean different things to different people in different situations. Therefore, failure can have a useful meaning only if it is expressed in reference to a given level of network performance. Failure of network performance usually will be defined as falling below the least acceptable level of service.

Using an assumed attenuation law for a given earthquake, it is relatively simple to find the failure probability of a component of a network, or a basis network system (system in series or in parallel, each consisting of a single input and a single output). For a more complex network, the task of finding the probability of network failure becomes more complex. These difficulties also increase as the requirement of the least acceptable level of network performance (objective) becomes more demanding and stringent. Therefore, it will be beneficial if any given network can be transformed into an equivalent simple network. It is demonstrated that any given network with a set of performance requirements can be transformed into another network with a single input-output pair, and the only requirement is the ability to go from input to output of the equivalent network [8]. The only basic network of special interest to the present work is a network of series systems in parallel (SSP) with a certain number of tie-sets (NT). Then, the following problem is addressed: find the probability that at least q out of NT fail simultaneously due to threats from a given set of sources in areas with known histories of earthquakes, where q is related to the least acceptable performance. A case study is shown in Fig. 1-2 [8].

In order to assess damage probability required to study the network failure statistics, probability damage matrices as defined in [26] have been applied. These damage matrices are often a consensus of best guesses by panels of experts, based upon past experience and observations in a given urban area.

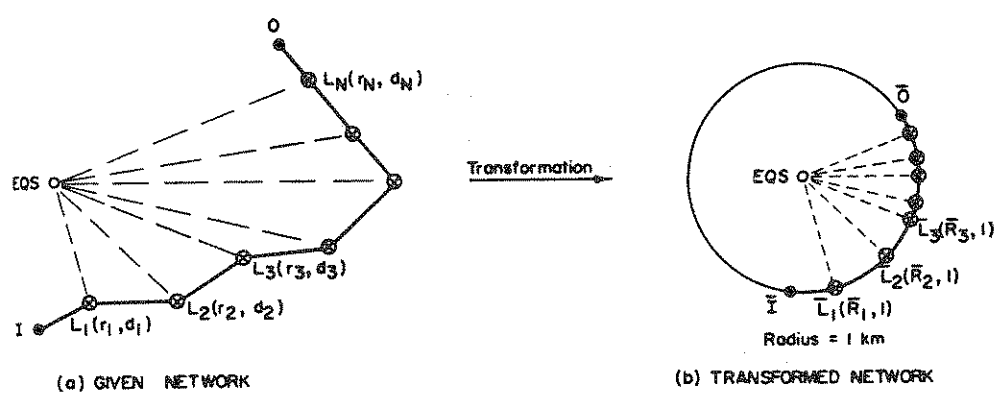

Figure 1-2 Topographical Transformation of a Discrete Basic Network in Series

1.2.3 Minimum Tree Method

R. Isoyama et al. [22] developed a practical method for simulating the post-earthquake restoration process of a city gas supply system. The restoration process of a middle-pressure gas network is simulated by using the concept of a minimum tree of network theory, which determines the restoration order under a given strategy.

The order of priority for restoration of the middle-pressure pipeline (called link) is determined by making a global judgement about the nodes (district regulators). The technique making use of the network theory is proposed for examining the factors of various kinds related to the determination of the order of priority of the restoration process. The factors related to the link are given to each link in term of link distance, and used to obtain the shortest route from each node to the source (gas plant). Furthermore, the weight of the link is calculated by superposing the node factors, in the form of weight, to the said shortest route. The order of priority for restoration of the link is determined from the magnitude of the link weight.

After the favorable routes from every demand node to a source on the network are determined, the higher the frequency of use of a given link, as a favorable route for accessing many demand nodes, the higher the degree of priority of the link in question.

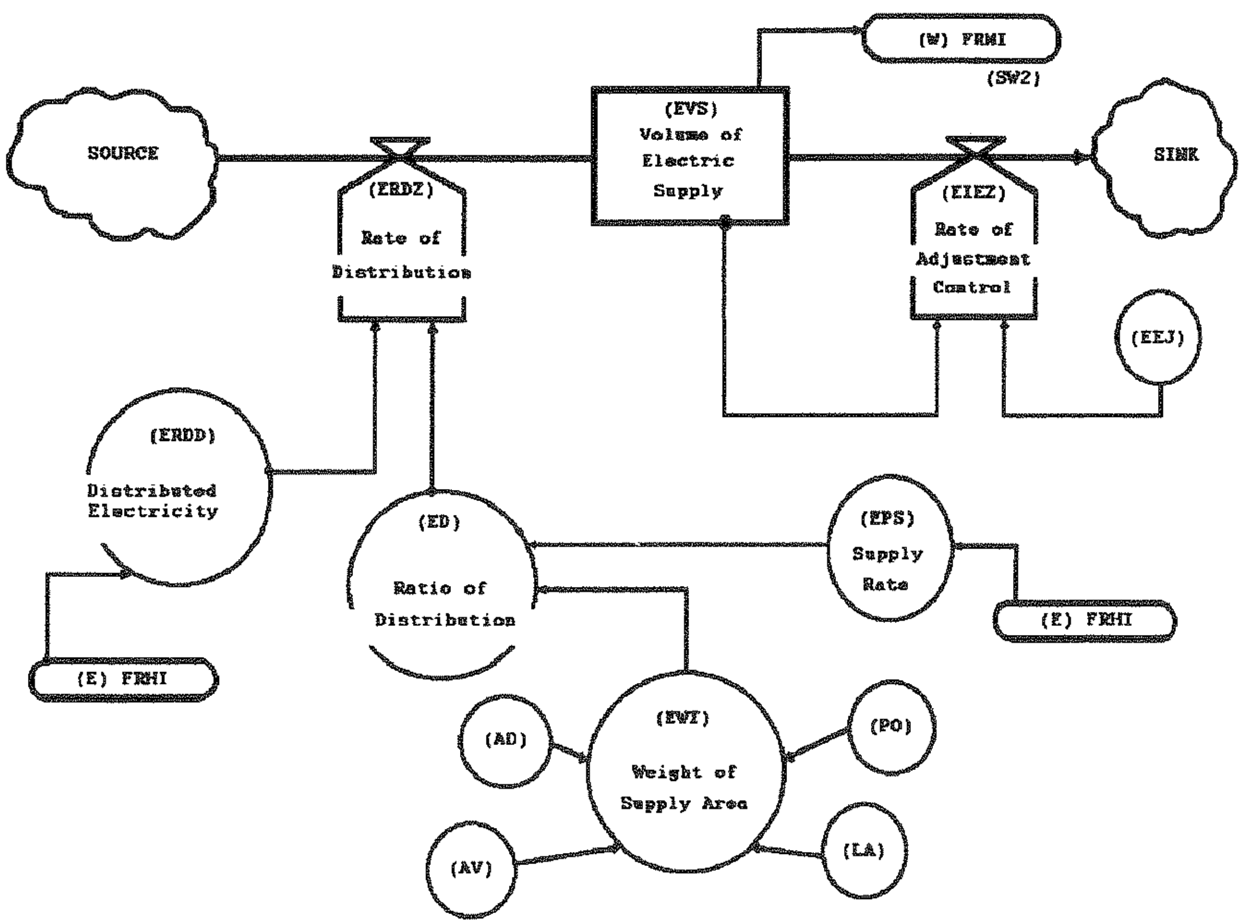

Figure 1-3 Functional Restoration Model for Power Supply System

1.2.4 System Dynamics Method

Hoshiya et al. [20] presented a system dynamics model to evaluate lifeline performance after an earthquake for a water supply network and an electric power supply network. By this model, if the initial state of damage distribution of both systems due to earthquake is given, and if the restoration strategy during post-earthquake recovery period is specified, the lifeline performance is simulated in terms of percentages of the corresponding normal supply of water or electricity supply quantity.

The main features of this performance evaluation model are illustrated in Fig. 1-3 [20], where each main flow consists of levels and their controlling values. By this model, it is possible to forecast the state of functional restoration of electric power and water supply system.

1.2.5 Objective Optimization Method

In papers by Jacobsen and Shinozuka, [15, 21] optimization problems dealing with water transmission and distribution systems have been studied. In Jacobsen's paper, the water distribution network synthesis problem can be described as follows: given various water supply locations and various water demand locations, the problem is to choose an optimal way to connect supply and demand locations, considering the potential seismic risk. The word "optimal" refers to minimizing construction costs plus discounted future earthquake damage costs subject to constraints which require that water demands, at various locations, be satisfied. Computed with the above approaches, which focus on "failure" or "success," this method is mainly concerned with future damage cost to the system and how changes in system design affect future damage costs, as well as initial construction costs. In particular, the goal of the research is to develop a means of calculating, in advance, future damage costs due to earthquakes, and the design of the system. Such information, together with initial construction costs, provides the means by which an optimal network can be designed.

1.2.6 Probability Importance

Yamada, et al, [19] developed a methodology to prepare rational countermeasures for seismic damage to lifeline systems, based on concepts of probabilistic importance. Probabilistic importance is defined as the rate at which system reliability improves as the reliability of the i-th link improves. This importance is expressed as follows;

$$I_i(t) = \frac{\partial g\,(q_i(t))}{\partial q_i(t)} \tag{1-1}$$

where g and q_i represent the unreliabilities of the system and the i-th link, respectively. $I_i(t)$ is the probability that the system is in a state at time t in which the functioning of the i-th link is critical; i.e., the system functions and fails when the i-th link functions and fails, respectively.

Based on this concept, various measures are applied to evaluate importance ranking of lifeline system components and cut sets in fault trees. Then, the importance order of the lifeline system components can be used to determine the restoration priority during the post-earthquake reconstruction process.

1.2.7 Markov Transition Model

Hoshiya [20] developed a theoretical formulation of lifeline restoration processes to evaluate a lifeline's functional performance in the post-earthquake period on the basis of a discrete-state discrete-transition Markov process. Given a fixed transition rate value, this model can evaluate the time required to restore the damaged lifeline system to some specific state or capacity. An underground water pipeline system in the city of Tokyo is chosen as a case study. The macroscopic system performance was evaluated in terms of the expectation of the restoration as a function of time.

1.3 Objective of this Investigation

The objective of this study is to understand the lifeline system's response to a major earthquake, the interactions among various subsystems, and by so doing, provide knowledge that could be useful in earthquake mitigation and preparedness planning. Previous studies in lifeline earthquake engineering have centered on the following problems: [2, 3, 4]

a. Identification of hazard prone system components;
b. Evaluation of lifeline performance after earthquakes;
c. Determination of restoration order of lifeline components;
d. Optimization of some system variables such as maximizing the total recovery area in given time limit.

While much effort has been applied to evaluate the dynamic response of lifelines to earthquakes, we note that the overall problem of lifeline system response has apparently not been studied as a complete urban system. For instance, mitigation policies for buildings and structures may influence the ability of the area's transportation and communication networks to remain functional. A holistic view of the situation, however, might provide insight into whether mitigation policies for strengthening structures, or provisions for establishing alternative emergency patterns of transportation and communication will prove most beneficial for reducing losses due to an earthquake. Besides, failure of some lifelines in certain sub-areas may only cause inconvenience, but the complete failure of the lifeline in the entire system will bring about disaster. For instance, if a water system only fails in some districts, the people in those areas can get water from adjacent districts. But if the system fails completely or fails in most areas, the supply of potable water rapidly becomes insufficient for sustaining needs. Furthermore, the emergency management authority should have some priority list for the consideration of limited resources and the importance order of the subsystems when they construct a response plan.

It is not possible to understand the impacts of mitigation and preparedness strategies without integrating the many disciplinary studies concerning earthquakes into a comprehensive view of the situation. This investigation considers the lifeline system as a complex, multidimensional, stochastic and dynamic system during the reconstruction period following a major earthquake. The analysis includes examination of dynamic capacity evolution of multiple lifeline systems, and the factors affecting the evolution process. In particular, we develop a general methodology to evaluate the restoration process of the lifeline system in the post-earthquake period. The goal of the method is to optimize the distribution of limited reconstruction resources, including materials and man-power, and to maximize the total economic return from the functioning of the repaired lifeline system. Markov decision process is used as the main tool, and an urban model technique based on a spatial economic model is also employed to represent the spatial distribution of lifeline capacity among the distinct subsystems.

SECTION 2
METHODOLOGY

2.1 Markov Decision Process

2.1.1 Markov Process and Markov Chain

A Markov process is a stochastic process with Markovian memoryless property. Let $(X_t\ t \geq 0)$ be a discrete random process with state space $S_x = \{0, 1, 2, ...\}$. Consider

$$0 < t_1 < t_2 < t_3 < t_4 ... < t_n$$

and

$$P\{X_{tn} = k_n \mid X_{tn-1} = k_{n-1} \quad ,..., X_{t1} = k_1\} \tag{2-1}$$

where k_j, j = 1, 2..., n are any nonnegative integers. If for all such t_j and k_j we have

$$P\{X_{tn} = k_n \mid X_{tn-1} = k_{n-1},..., X_{t1} = k_1\} = P\{X_{tn} = k_n \mid X_{tn-1} = k_{n-1}\} \tag{2-2}$$

then the sequence $\{X_t,\ t\ 0\}$ is called a Markov process. Equation (2-2) defines the Markov property. The distinguishing feature expressed by (2-2) is that the future value of X_{tn} only depends on the last known value of X_t, namely X_{tn-1}, and is independent of all previous values.

A Markov chain is a Markov process with discrete state space, and the Chapman-Kolmogorov equation for a Markov chain takes the following form for any times s > t > u ≥ 0 and states j and k:

$$p_{jk}(u, s) = \sum_i p_{ji}(u, t) * p_{ik}(t, s) \tag{2-3}$$

where "*" denotes multiplication and p_{jk} (u, s) is the probability of moving from state j to k in time beginning at u and ending at s, and the summation is over all states of the chain. The basic concept of the Markov chain are those of "state" of a system and state "transition." To study Markov chains, we must specify the probabilistic nature of the state transition. It is convenient to assume that the time between transition is a constant. Suppose that there are N states in the system numbered from 1 to N. If the system is a simple Markov process, then the probability of a transition to state j during the next time interval, given that the system occupies state i, is a function only of i and j and not of any history of the system before its arrival in i. In other words, we may specify a set of conditional probabilities p_{ij} that a system which now occupies state i will occupy state j after its next transition. Since the system must be in some state after its next transition, then

$$\sum_{j=1}^{N} p_{ij} = 1 \qquad i = 1, 2, ..., N$$

where the probability that the system will remain in i, p_{ii}, has been included. Since the p are probabilities,

$$0 \leq p_{ij} \leq 1$$

Considering all iεN, we have the following transition matrix

$$P = \begin{vmatrix} p_{11} & p_{12} & \cdots\cdots & p_{1,N-1} & p_{1N} \\ p_{21} & p_{22} & \cdots\cdots & p_{2,N-1} & p_{2N} \\ & & \cdots\cdots & & \\ p_{N-1,i} & p_{N-1,2} & \cdots & p_{N-1,N-1} & p_{N-1,N} \\ p_{N1} & p_{N2} & \cdots & p_{N,N-1} & p_{NN} \end{vmatrix} \tag{2-3}$$

The transition matrix P is thus a complete description of the stationary Markov chain. We make use of this matrix to answer all questions about the process. For instance, we may wish to know the probability that a system will be in state i after n time periods if we know the system is in state j at the beginning of the n time period. To answer this and other questions, we define a state probability $p_i(n)$, the probability that the system will occupy state i after n transitions if its state at n=0 is known. It follows that

$$\sum_{i=1}^{N} p_i\ (n) = 1 \tag{2-4}$$

$$p_j\ (n+1) = \sum_{i=1}^{N} p_i\,(n) * p_{ij} \qquad n = 0, 1, 2,... \tag{2-5}$$

If we define a row vector of state probabilities $\overline{p}\,(n)$ with components $p_i(n)$, then

$$\overline{p}\,(n+1) = \overline{p}\,(n) * P \qquad n = 0, 1, 2,... \tag{2-6}$$

Since by recursion we have have

$$\begin{aligned} \overline{p}\,(1) &= \overline{p}\,(0) * P \\ \overline{p}\,(2) &= \overline{p}\,(1) * P = \overline{p}\,(0) * P^2 \\ \overline{p}\,(3) &= \overline{p}\,(2) * P = \overline{p}\,(0) * P^3 \\ &\cdots\cdots\cdots\cdots \end{aligned} \tag{2-7}$$

In general, we have

$$\bar{p}(n) = \bar{p}(0) * P^n \qquad \text{for the stationary chain } n = 0, 1, 2... \tag{2-8}$$

Thus it is possible to find the probability that the system occupies each of its states after n moves, $\bar{p}(n)$, by postmultiplying the initial state probability vector $\bar{p}(0)$ by the n-th power of the transition matrix P.

2.1.2 Markov Decision Process

A Markov decision process is a stochastic sequential process. Consider a system that can be described by a discrete time Markov chain, where, furthermore, the decisions of each epoch and the returns are associated with each state we observe. Suppose a system whose state space has finitely many states. Let a state space S be a set of states labeled by the integers i=1, 2,...,N. That is, S = {1, 2,...,N}. For each $i \varepsilon S$, we have a set of K_i of finite actions (or alternatives) labeled by the integers $k = 1, 2,..., K_i$.

The policy space is denoted by the Cartesian product of each action set, that is $K = K_1 \times K_2 \times ... \times K_N$. Next, consider a sequential decision problem; that is, periodically observe one of the states at time t=0, 1, 2,..., and make a decision at each time.

When the system is in state $i \varepsilon S$ and we make an action $K \varepsilon K_i$, two things happen: (1) we obtain the return r_i^k and (2) the system transits to state j obeying the probability law $p_{ij}^k (j \varepsilon S)$ at the next time, given that system is in state i at that time and action k is made. Here we assume that the return r_i^k is bounded for all $i \varepsilon S$ and $k \varepsilon K_i$.

We also give an initial state distribution

$$\bar{p} = ({}_1p_o \, , {}_2p_o \, ,..., {}_Np_o) \tag{2-9}$$

where

$$\sum_{i \varepsilon S} {}_ip_o = 1 \qquad {}_ip_o \geq 0 \qquad \text{for all } i \varepsilon S$$

The system is then a nonstationary Markov chain with returns. Our problem is to find strategies that maximize the total expected return over a finite-time or an infinite-time ($n \rightarrow \infty$) horizon, where a strategy is a sequence of decisions in each time and each state. Let F be a set of functions from the state space S to the policy space K. Since S and K are both finite sets, F is a finite set. Let f be a function in F, then a strategy U is defined by a sequence $\{f_n \, , \; n=1, 2,...\}$. Hence, we may write a strategy

$$U = \{f_1 \, , f_2 \, , \, ... \, , \, f_n \, , \, ...\} \tag{2-10}$$

where f_n is the decision vector for each state at time n; that is, $f_n(i)$, the i-th element of f_n, is an action of state $i \varepsilon S$ at time n.

For any strategy U, we have a nonstationary Markov chain. Thus we write the n-step transition probability matrix as

$$P_n(U) = P(f_1)*P(f_2)*...*P(f_n) \quad \text{for } n = 1, 2,... \tag{2-11}$$

where $P(f_n)$ is the N x N transition matrix whose i-jth element is p_{ij}^k , $k=f_n(i)\varepsilon K_i$. For n=0, we define $P_o(U) = I$ (the N x N identity matrix). For any $f \varepsilon F$, we may write the N x 1 return vector r(f) whose i-th element is r_i^k , $k=f(i)\varepsilon K_i$. Under the notation defined above, let R be economic return, we have the N x 1 total expected return vector, ER, starting in each state $i\varepsilon S$:

$$ER(U) = \sum_{n=0} p_n (U) * \bar{r}(f_{n+1}) \tag{2-12}$$

Then, Markov decision process can be described as to choose an optimal strategy U*, which satisfy the vector inequality

$$ER(U^*) \geq ER(U) \tag{2-13}$$

There are three main algorithms to find an optimal strategy for a Markov decision process [25].

a. Howard's policy iteration algorithm;
b. Linear programming algorithm;
c. Dynamic programming algorithm.

For the models with a finite-time horizon, dynamic programming is very useful. Since one application of Markov decision processes is confined to finite-time horizon, we shall present a detailed discussion of the dynamic programming algorithm.

2.1.3 Dynamic Programming Algorithm

Using the same notation that we used in the preceding section, we first define a policy. A policy U is a sequence $(.....,f_n, \;....,f_2, f_1)$ of members of F, where f_n is the decision for each state. That is, $f_n(i)$ is an action in state i measured n time backward from the end of the planning horizon. A policy U describes a backward sequence of actions in each state ending with f_1. The total expected return using n times of strategy U starting in each state $i\varepsilon S$ is

$$\overline{V}_n(U) = \bar{r}(f_n) + P(f_n)\,\bar{r}(f_{n-1}) + ... + P(f_n)P(f_{n-1}) ... P(f_2)\bar{r}(f_1) \tag{2-14}$$

for $n \geq 1$, where $\overline{V}_n(U)$ is the N x 1 column vector whose i-th element is the total expected return using n times of starting in state $i\varepsilon S$. From (2-14) we have the following recurrence relation:

$$\overline{V}_n(U) = \overline{r}(f_n) + P(f_n) * \overline{V}_{n-1}(U) \qquad (2\text{-}15)$$

for $n \geq 1$, where $V_o(U) = 0$.

To find an optimal policy U*, we make use of dynamic programming, in particular, the principle of optimality. The principle of optimality states that an optimal policy has the property that despite the initial state and initial decisions, the remaining decisions must constitute an optimal policy for the state resulting from the first decision. Applying the principle of optimality, we have the following recurrence formula:

$$V_{n+1}(U^*)(i) = \max_{k \varepsilon K_i} \left[r_i^k + \sum_{j \varepsilon S} + p_{ij}^k * V_n(U^*)(j) \right] \qquad (2\text{-}16)$$

for all $i \varepsilon S$ and for all $n \geq 0$, where

$$V_o(U^*)(i) = 0 \qquad (2\text{-}17)$$

for all $i \varepsilon S$. Here $V_o(U^*)(i)$ is the ith element of $V_n(U^*)$. We can immediately obtain an optimal policy from (2-16) and (2-17).

2.2 Spatial Economic Model

During the past two decades, models of urban and regional evolution have been a topic of many studies in city planning. The main objective of these studies is to construct land use, development or spatial location models that describe or predict the geographical distribution of industry, commerce and residential population throughout an urban area. It is considered that if such models were successful, they could beneficially be used to predict future growth trends and determine, before the fact, the effect of various structural changes in the urban area. It is obvious that this ability would prove very useful to city and transportation planners, other government agencies, utilities and many commercial and service organizations.

Although urban and social systems have long been studied as having basic, nonlinear, dynamic properties in which the decisions of their human actors play an essential role, until recently, the conceptual and mathematical foundations for a substantive, scientific inquiry within that context have been lacking. The failure (or lack of sufficient success) of a number of urban systems projects during past decades have caused scientists to look for a new approach from conventional perception.

From the beginning of the 1980's, some new concepts have emerged from natural science related to the self-organization, or structural evolution, of complex systems. The new approach attempts to meet the nonlinear dynamic aspects of social systems. Having its roots in non-equilibrium analysis, the new approach mainly considers the evolution of a complex system as the result of interaction among the system components, and the evolution is not a deterministic process. For urban dynamics we can not build a clear, objective, quantified function. What we can do is perform an exploration of all possible futures, examining the stability and resilience of the various paths.

Based upon this philosophy, P.M. Allen et al. [5] developed the so-called spatial economic model. In the spatial economic model, a system is regarded as a group of subsystems. The difference between the system's goal and the state of the existing system, as well as the difference among the attributes of the subsystems, or in other words, the interaction among the subsystems, are the impetus of the evolution of the system. The evolution process of the system depends upon the attractivity of the subsystem to the system goal with some probability. The mathematical expressions of the spatial economic model are diversified for different situations. One of Allen's models is the following logistic equation:

$$\frac{dX_i^1(t)}{dt} = \partial * X_i^1(t) * \left[1 - \frac{X_i^1(t)}{\beta} \right] \tag{2-18}$$

where ∂, β are terms that depend upon the system being studied.

This is a potential starting point for future stochastic evolution studies. However, we shall go directly to the probabilistic formulation through Markov chains, thus by-passing Allen's dynamical equation formulation.

SECTION 3
PROBLEM FORMULATION

3.1 Introduction

Urban areas have a number of lifeline systems, some of which are categorized as follows:

Energy:	electricity, gas, liquid fuel
Water:	potable, flood, sewage
Transportation:	highway, railway, airport, harbor
Communication:	telephone and telegraph, radio, mail

Most lifelines consist of sources, major transmission lines, storage, and distribution or collection systems. Lifelines represent approximately 50% of the economic value vulnerable to an earthquake in an urban area. Past earthquake experience has demonstrated repeatedly that lifeline failure can produce severe consequences to the urban area. Examples of these consequences include:

a. Loss of service of the utility;
b. Direct financial loss;
c. Suspension of certain human activity, such as social activities, entertainment, commercial, etc.;
d. An inability to cope with secondary disaster such as fires, famines, and epidemics; and
e. Failure of a nature such that a lifeline itself becomes a hazard to life and property.

More specifically, essential lifeline interruptions can have immediate and serious effects upon a population, since:

a. Damaged transportation systems can impede evacuation or the arrival of disaster relief personnel and supplies;
b. Ruptured gas lines and severed electrical cables can be catalysts for fire;
c. Damaged water lines, storage tanks, and aqueducts can hamper fire fighting efforts and make potable water a rare commodity;
d. Ruptured sewer lines, municipal sewage tanks, and septic tanks can contaminate drinking water and render home toilets inoperative;
e. Downed telephone lines or damaged equipment can make it difficult for people in a stricken area to contact relatives and vice versa, or to immediately contact emergency relief agencies;
f. The interruption of gas and electrical service can make it difficult to heat or cool buildings, prepare food or boil water; and
g. All of the above can interrupt vital health services.

Past experience has shown that it can take weeks or even months to fully restore damaged lifeline services and years for the complete restoration of a destroyed source facility or distribution network. Damaged lifeline systems cannot satisfy all demands for the entire area before being completely restored. Additionally, the reconstruction resource is limited within the repair period. Therefore, the emergency management authority should assign different priorities of rescue operation for each subarea in order to minimize the total losses caused by malfunction of lifeline systems in whole urban areas (or, maximize the total return from the function of repaired lifeline system).

3.2 Problem Modeling

3.2.1 Basic Consideration

For post-earthquake reconstruction problems, we have the following consideration.

The reconstruction process of urban lifeline systems due to a major earthquake is a complex process, which involves both determinism and chance. The former is associated with available rescue resources, demand and supply for lifeline, and damage degree of system components. The latter includes secondary events, the interaction among the subsystems and other uncertainties. After a supposed catastrophic earthquake occurs, the lifeline systems may be severely destroyed and unable to function to capacity. The lifeline system cannot meet the requirements for demand from all subareas. When the emergency management authority develops mitigation and response plans for lifeline systems, the following basic facts should be taken into account.

a. An urban area consists of a number a subareas which are geographically formed with some specific characters, such as business, residential, industry, military and special districts (dam, nuclear plant, and so on). Thus, each subarea has a different importance order, economic and social, for the function of the whole urban area.

b. Because it is not possible to restore the damaged lifeline systems in all subareas simultaneously, the short supply of various lifelines to different subareas is inevitable. Furthermore, the returns from function of repaired lifeline systems in different subareas are quite different for the consideration of each subarea having different economic importance order.

c. The reconstruction resource varies during the entire restoration period since the available resource may be influenced by government aid and other factors.

d. The interaction among the subsystems may dramatically affect the restoration process in the entire area. For instance, the failure of a power system in subarea i may make it impossible to repair the water and transportation systems in subarea i as well as in the surrounding subareas.

Therefore, the decision-maker of reconstruction policy should answer the question: given limited rescue resources, including material and man-power, varying in each repair stage, how should they be assigned to different subsystems, considering the uncertainties involved in restoration process, in order to maximize the total return from functioning of a repaired lifeline system. This is a stochastic sequence decision problem. Markov decision process is a natural methodology to formulate and solve this kind of problem.

3.2.2 Capacity State of Subsystem

Let S(t) be the restoration process of a lifeline system indicating a level of state at time t after earthquake occurrence. Consider an urban system composed of N subsystems; we assume N_A subareas, and N_L lifelines. For simplicity of discussion, we set N_A x N_L = N subsystems. Thus, for example, for $N_A = 4$, $N_L = 2$, we shall consider a total of N = 8 subsystems. Then observe the capacity state $_nS(t)$ at time t of the nth subsystem. The capacity state $_nS(t)$ is assumed to take one of M different levels S_1, S_2,...,S_M dependent upon the degree of damage and the degree of restoration process, where S_i indicates the level of complete failure and S_M stands for the level of normal state, or full capacity. The intermediate states S_i , i = 2, 3, ..., M-1 indicate the level of damage, or capacity loss in the descending order.

Now imagine a time dependent variation of the restoration $_nS(t)$ shown in Figure 3-1. All subsystems start at level $_nS(0)$ at the instance of earthquake occurrence and are then restored to the normal state $_nS_M$ after some time. The total time required for the full restoration in given by T_M. Since the initial state at time t = 0 of $_oS(O)$ n = 1, 2,...,N is governed by chance and the restoration process involves many uncertainties, $_nS(t)$ are assumed to be random processes. Furthermore, since the present state $_nS(t)$ of the nth subsystem may depend upon the state at one step previous in time and is independent of any other previous times, we represent $_nS(t)$ as a discrete-state discrete-time Markov process (Markov chain).

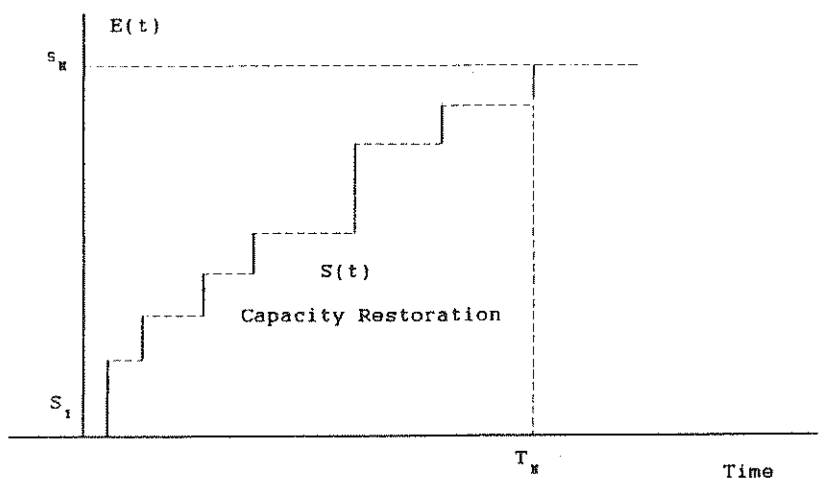

Figure 3-1 Restoration Curve of S(t)

The transition matrix is fundamental in the formulation of Markov chains. We assume the transition probabilities are functions of assigned rescue resource, geographical condition and structural character of the lifeline system. The transition probability may be written as

$$ {}_nP_{ij}\,(x_n\,,\, t+\Delta t) = \text{Prob}\,\{{}_nS(t+\Delta t) = j \mid {}_nS(t) = i \text{ and } x_n \text{ unit resources.}\} \tag{3-1}$$

The transition matrix whose components are ${}_np_{ij}(x_n,k\Delta t)$ is given as follows,

$$ {}_nP(x_n\,,\,k\Delta t) = \begin{vmatrix} {}_nP_{11}(x_n\,,\,k\Delta t)\;{}_nP_{12}(x_n\,,\,k\Delta t).....{}_nP_{1m}(x_n\,,\,k\Delta t) \\ {}_nP_{21}(x_n\,,\,k\Delta t)\;{}_nP_{22}(x_n\,,\,k\Delta t).....{}_nP_{2m}(x_n\,,\,k\Delta t) \\ .... \\ .... \\ {}_nP_{m1}(x_n\,,\,k\Delta t)\;{}_nP_{m2}(x_n\,,\,k\Delta t).....{}_nP_{mm}(x_n\,,\,k\Delta t) \end{vmatrix} \tag{3-2}$$

We assume the restoration process ${}_nS(k\Delta t)$ is a non-decreasing process either staying at the present state or shifting, by one step, to the next higher state during a time interval Δt. Thus, the probability transition matrix (3-2), assuming that state m is an absorbing state (no further increase possible), may be written as:

$$ {}_nP(x_n\,,\,k\Delta t) = \begin{vmatrix} 1-{}_np_{12}(x_n\,,\,k\;t)\;{}_np_{12}(x_n\,,\,k\Delta t) & & \\ & 1-{}_np_{23}(x_n\,,\,k\Delta t)\;{}_np_{23}(x_n\,,\,k\Delta t) & \\ & .... & \\ & .... & \\ & & 1-{}_np_{m-1,\,m-1}(x_n\,,\,k\Delta t)\;{}_np_{m-1,\,m}(x_n\,,\,k\Delta t) \\ & & 1 \end{vmatrix} \tag{3-3}$$

If the probability that ${}_nS\;(k\Delta t) = S_j$ is expressed by ${}_np_j(k\Delta t)$, then the probability state vector is given by

$$ {}_n\overline{S}\,(k\Delta t) = [{}_np_1\,(k\Delta t)\;,\;{}_np_2\,(k\Delta t)\;,\;...{}_np_M\,(k\Delta t)] \tag{3-4}$$

where $\sum_{j=1}^{M} {}_np_j\;(k\Delta t) = 1.0$ for each $k = 0, 1, 2,...$.

The initial probability state vector, ${}_nS(0)$ must be evaluated from seismic risk analysis. If ${}_nS(0)$ is given, we can use equation (3-3) and (3-4) successively to determine

$$ {}_n\overline{S}\,(x_n\,,\,k\Delta t) = {}_n\overline{S}\,(0) * {}_nP(x_n\,,\,\Delta t) * {}_nP(x_n\,,\,2\Delta t)...{}_nP(x_n\,,\,k\Delta t) \tag{3-5}$$

Equation (3-5) gives the probability law of the capacity restoration state of the nth subsystem at time t = k t in the post-earthquake recovery period.

3.2.3 Economic Return

Let ${}_n\overline{R}$ be the immediate economic return vector for subsystem N at capacity state i, i = 1, 2, 3,..., M,

$$ {}_n\overline{R} = [{}_n r(1) , {}_n r(2) ..., {}_n r(M)] \qquad (3\text{-}6) $$

We assume the immediate return is only a function of the system state and will take different values for distinct states. Because we cannot predict the exact state that the lifeline may be in after some time restoration period, we shall study the expected value of the economic return from functioning of lifeline systems.

$$ {}_n G (x_n) = {}_n\overline{R} * {}_n\overline{S} (x_n , k\, t)' \qquad \text{("' " denotes transition)} \qquad (3\text{-}7) $$

The expected return ${}_nG(x_n)$ is a function of allocated resource and immediate return.

3.2.4 Optimal Allocation of Limited Resources

Dynamic programming is used to optimize the limited rescue resource distribution among various subsystems. In the following discussion, ${}_nG(x_n)$ is the only criterion for optimizing the rescue resource distribution during the post-earthquake restoration process. In order to use dynamic programming, we must make the following assumptions:

a. All rescue resources can be expressed in a common unit, such as monetary unit;
b. After a catastrophic earthquake, the available rescue resources are limited in each time period;
c. The return from each subsystem is independent of the resource allocation to the other subsystems;
d. The return functions are nondecreasing; and
e. The total return from all subsystems is equal to the sum of the individual returns.

With these assumptions, dynamic programming can be applied to the lifeline reconstruction process. In order to develop the dynamic programming functional equation for the resources allocation problem, we denote

$R(x_1, x_2, x_3,...,x_n)$ = total return from allocating x_n units of resource to the nth subsystem n = 1, 2,..., N.

${}_nG(x_n)$ = expected return from nth subsystem when x_n units of rescue resource are allocated to that subsystem.

x^* = maximum number of units of resource available to allocate to the whole system.

Then the problem we want to solve is

$$\text{Max } R(x_1, x_2, \ldots x_n) = \text{Max} \sum_{n=1}^{N} {}_n G(x_n) \qquad (3\text{-}8)$$

subject to $\sum_{n=1}^{N} x_n = x* \;\; ; \;\; x_n \geq 0.$

Equation (3-8) is solved by dynamic programming.

SECTION 4
SIMULATION

4.1 Simulation Flow Chart

The restoration of lifeline systems in the post-earthquake period is a complex, multidimensional process, involving many uncertainties. In addition, there are many factors that influence the restoration process of lifeline systems. Computer simulation is one approach to dealing with this kind of problem. By computer simulation, the combination of various scenario and reconstruction policies can be examined comprehensively. Then, optimal reconstruction policies under different situations can be inferred.

In our study, simulation has been divided into parts called "modules." A simplified block diagram showing the major modules is shown in Figure 4-1. Detailed discussions of simulation are in Section 5.

4.2 Numerical Examples

For simplicity, we set N = 8, M = 10 and the one step transition rate is assumed to be of the form

$$ {}_n p_j(x_n) = a_n * \{1 - \exp(-b_n * x_n * (0.1 * j)^{0.15})\} \qquad (4\text{-}1) $$

The one step transition rate plays an important role in Markov chain method. Proper selection of the transition rate is the key point of successful application of Markov chain methodology. But the reconstruction process of damaged lifeline systems after catastrophic earthquakes is so complicated that it is impossible to find a suitable formula without integrated investigation of the reconstruction process. In this simulation, we chose formula (4-1) according to the following considerations:

a. The one step transition rate is the probability of a system changing from one state into another, so it must obey the probability law, i.e. $0 \le p_j\,(x_n) < 1$.

b. The one step transition rate is a function of assigned resource. The more resource that is given to a system, the higher will be the transition rate for the system.

c. The one step transition rate will be affected by the geographical and structural conditions of the restored systems. In other words, the transition rate will be variable for distinct systems even with the same amount of resources.

d. The state of a damaged lifeline will have some influence on the transition rate of the system. The last term in formula (4-1) takes this factor into account.

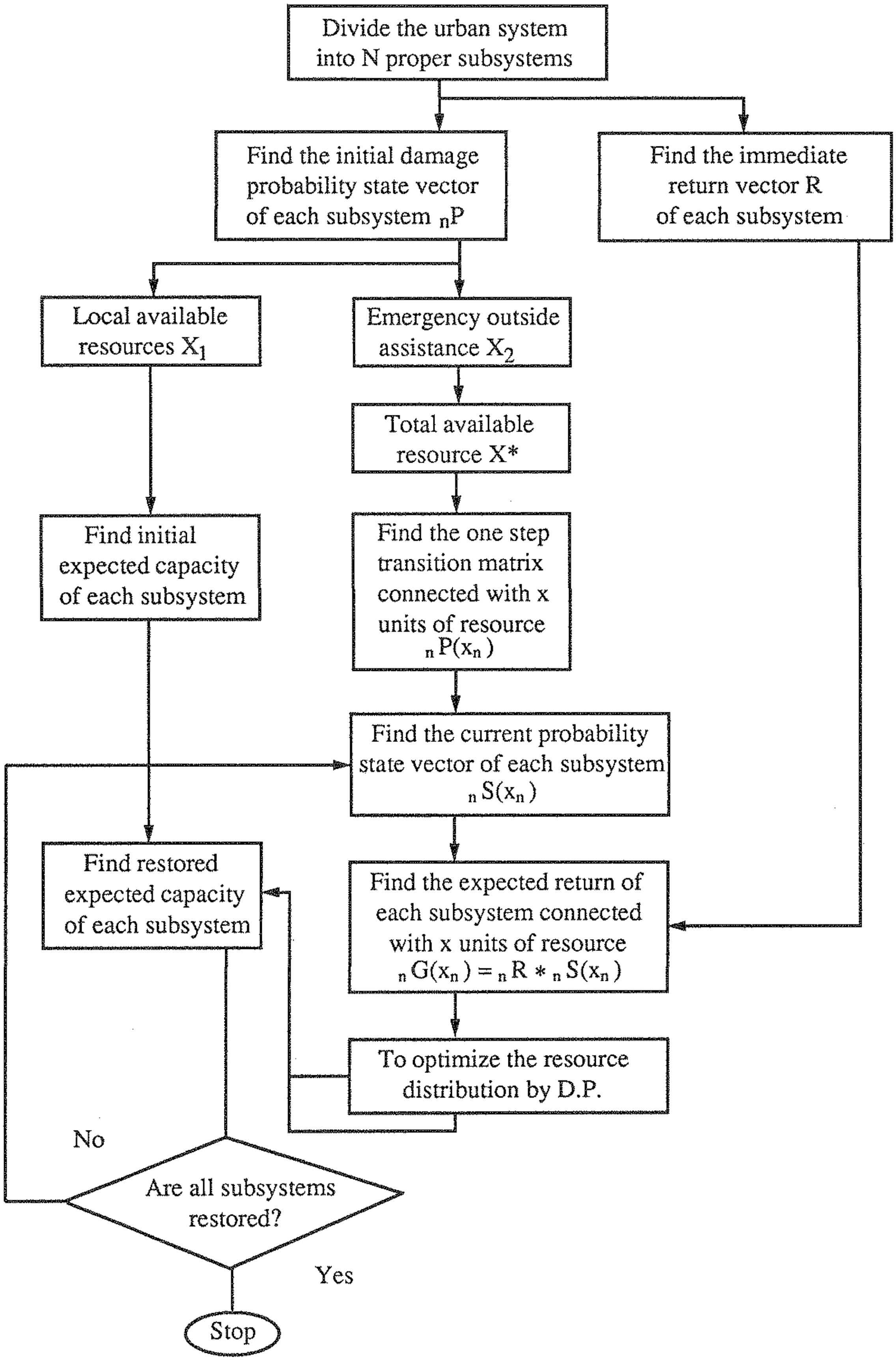

Figure 4-1 Simulation Diagram of Lifeline System Restoration Process

The total available resource in each restoration period is allowed to be variable and the restoration time T = 46 is assumed. Using the immediate return of subsystems in Table 4-I, different scenarios are designed to check the influence of various factors involved in the restoration process of lifelines in the post-earthquake period. The simulation was carried out with an IBM 4341 VM/CMS computer. The computer program is listed in the Appendix. The program consists of three main parts. Main routing manages the simulation environment, data input and result output. The second routing is to calculate the one step transition matrix, which is a function of available resource. The third routing is a typical dynamic programming subroutine which decides the optimal distribution of limited resource.

Table 4-I Immediate Return of Subsystem N at Different Capacity i

N\i	1	2	3	4	5	6	7	8	9	10
1	0	10	15	30	38	50	55	65	70	75
2	0	10	20	38	45	55	65	67	69	70
3	0	10	10	10	10	15	16	17	19	20
4	0	15	20	20	25	35	35	38	40	45
5	0	10	12	22	23	35	37	40	45	45
6	0	5	15	20	25	30	35	40	45	60
7	0	7	9	16	18	22	30	35	45	55
8	0	1	2	11	20	25	35	38	45	60

4.2.1 Case 1

This case uses the initial probability state vector in Table 4-II and transition parameters, including geographical and structural data in the Table 4-III. In this case, the rescue resource in each repair period varies, as given in Table 4-IV. Table 4-V is the optimal distribution of resource for each subsystem over whole reconstruction period. Fig. 4-2 shows the dynamic evolution of each subsystem.

Table 4-II Initial Probability State Vector of Case 1

N\i	1	2	3	4	5	6	7	8	9	10
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9
2	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0
3	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.2	0.5	0.3	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.3	0.2	0.5	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.6	0.3	0.1	0.0	0.0	0.0	0.0
8	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4-III Coefficients of Transition Rate Probabilities

$a_1 = .85$	$a_2 = .75$	$a_3 = .93$	$a_4 = .72$	$a_5 = .95$	$a_6 = .61$	$a_7 = .81$	$a_8 = .85$
$b_1 = .12$	$b_2 = .185$	$b_3 = .095$	$b_4 = .166$	$b_5 = .145$	$b_6 = .196$	$b_7 = .16$	$b_8 = .09$

Table 4-IV Available Resource in Each Repair Stage for Case 1

11	13	16	15	21	27	36	36	36	36	34	33	30	30	30	27	27	24	23	23	21	20	15
27	27	29	28	25	24	13	15	19	19	19	19	18	18	18	18	17	17	17	16	16	16	16

Table 4-V Optimal Distribution of Resource Among N Subsystem During Each Repair Period

T\N	1	2	3	4	5	6	7	8	OPT.RET at T-th peri.	TOT.RET.OF T peri
1	1	5	1	1	1	1	1	0	218.34	218.34
2	1	5	1	1	3	1	1	0	224.09	442.43
3	1	5	1	2	5	1	1	0	230.49	672.92
4	1	4	1	1	6	1	1	0	236.08	909.00
5	1	4	4	2	6	2	2	0	243.06	1152.07
6	1	4	4	3	7	4	4	0	251.02	1403.08
7	1	5	4	4	9	6	7	0	260.37	1663.46
8	1	4	3	4	8	6	10	0	269.37	1932.82
9	1	3	2	4	8	7	11	0	278.31	2211.13
10	1	3	1	4	7	8	12	0	287.26	2498.39
11	1	2	1	4	5	8	13	0	295.88	2794.27
12	1	1	1	4	4	9	13	0	304.17	3098.44
13	1	1	1	4	2	9	12	0	311.59	3410.03
14	1	1	1	4	2	9	11	1	318.38	3728.40
15	1	1	2	4	2	10	9	1	324.38	4052.78
16	1	1	1	4	2	10	7	1	329.38	4382.16
17	1	1	2	4	2	10	6	1	333.85	4716.01
18	1	1	2	4	1	10	4	1	337.54	5053.55
19	1	2	2	4	1	9	3	1	340.74	5394.28
20	1	1	3	4	2	9	2	1	343.58	5737.86
21	1	1	3	4	1	8	2	1	345.94	6083.80
22	1	1	3	3	2	7	2	1	347.95	6431.74
23	1	1	2	2	1	6	1	1	349.36	6781.10
24	1	3	6	4	3	6	3	1	351.48	7132.57
25	1	2	7	4	2	6	2	3	353.37	7485.94
26	1	2	7	3	2	5	1	8	355.28	7841.22
27	1	1	6	2	1	3	1	13	357.31	8198.53

Table 4-V Optimal Distribution of Resource Among N Subsystem During Each Repair Period (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET at T-th peri.	TOT.RET.OF T peri
28	1	1	3	1	1	1	1	16	359.63	8558.16
29	1	1	1	1	1	1	1	17	362.49	8920.65
30	1	1	1	1	1	1	1	6	364.21	9284.85
31	1	1	1	1	1	1	1	8	366.36	9651.21
32	1	1	1	1	1	1	1	12	369.28	10020.50
33	1	1	1	1	1	1	1	12	372.31	10392.81
34	1	1	1	1	1	1	1	12	375.41	10768.21
35	1	1	1	1	1	1	1	12	378.54	11146.75
36	1	1	1	1	1	1	1	11	381.52	11528.27
37	1	1	1	1	1	1	1	11	384.51	11912.78
38	1	1	1	1	1	1	1	11	387.49	12300.27
39	1	1	1	1	1	1	1	11	390.46	12690.73
40	1	1	1	1	1	1	1	10	393.20	13083.93
41	1	1	1	1	1	1	1	10	395.89	13479.82
42	1	1	1	1	1	1	1	10	398.49	13878.31
43	1	1	1	1	1	1	1	9	400.82	14279.13
44	1	1	1	1	1	1	1	9	403.05	14682.18
45	1	1	1	1	1	1	1	9	405.16	15087.34
46	1	1	1	1	1	1	1	9	407.13	15494.47

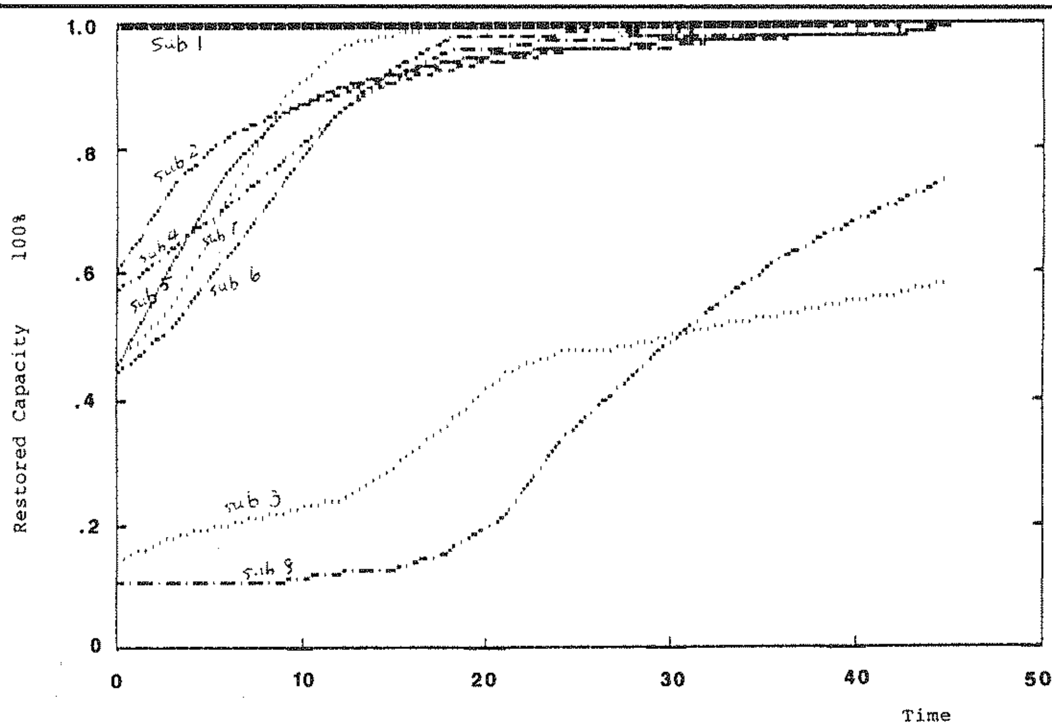

Figure 4-2 Restoration Curve of Lifelines in Case 1

4.2.2 Case 2

Case 2 uses the same data as in Case 1, except the initial probability state vector for some subsystems has been changed. Subsystem 1 changes from fully functional to totally destroyed and subsystem 8 from totally destroyed to a nearly functional state, so the influence of the initial damage state on the reconstruction policy can be seen. The supposed initial probability state vector for Case 2 is in Table 4-VI and Table 4-VII is the optimal distribution of rescue resource. Figure 4-3 shows the dynamic evolution of each subsystem.

Table 4-VI Initial Probability State of Case 2

N\i	1	2	3	4	5	6	7	8	9	10
1	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0
3	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.2	0.5	0.3	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.3	0.2	0.5	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.6	0.3	0.1	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	0.1	0.0

Table 4-VII Optimal Distribution of Resource Among the Subsystem N During Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	4	1	1	1	1	1	1	183.53	183.53
2	1	5	1	1	2	1	1	1	189.75	373.29
3	4	4	1	1	3	1	1	1	196.82	570.11
4	3	3	1	1	4	1	1	1	203.16	773.27
5	5	4	1	1	5	1	1	3	211.46	984.73
6	7	3	1	1	6	2	1	6	221.49	1206.22
7	9	3	2	2	6	3	3	8	234.06	1440.28
8	11	2	1	2	5	3	4	8	246.51	1686.79
9	12	2	2	1	5	3	5	6	258.86	1945.65
10	13	1	1	1	4	4	7	5	271.16	2216.80
11	13	1	1	1	3	4	8	3	282.98	2499.79
12	13	1	1	1	3	4	8	2	294.56	2794.34
13	12	1	1	1	2	4	8	1	305.28	3099.62
14	11	1	1	1	2	5	8	1	315.73	3415.35
15	11	1	1	1	2	5	8	1	325.77	3741.12
16	10	1	1	1	1	5	7	1	334.57	4075.69
17	9	1	1	1	1	6	7	1	342.79	4418.48

Table 4-VII Optimal Distribution of Resource Among the Subsystem N During Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
18	8	1	1	1	1	6	5	1	349.76	4768.23
19	7	1	1	1	1	6	5	1	356.03	5124.26
20	7	1	1	2	1	6	4	1	361.84	5486.10
21	6	1	1	2	1	6	3	1	366.85	5852.95
22	5	1	1	2	1	6	3	1	371.34	6224.29
23	4	1	1	1	1	5	1	1	374.64	6598.93
24	5	1	1	4	3	7	3	3	379.63	6978.55
25	5	1	1	4	3	7	3	3	384.18	7362.73
26	5	1	3	5	3	7	2	3	388.55	7751.29
27	5	2	3	5	2	6	2	3	392.40	8143.68
28	4	1	2	5	2	6	2	3	395.59	8539.27
29	4	1	3	5	2	5	2	2	398.39	8937.65
30	1	1	1	3	1	4	1	1	399.91	9337.56
31	2	1	1	4	1	4	1	1	401.53	9739.09
32	3	1	3	4	2	4	1	1	403.37	10142.43
33	3	1	3	4	1	3	2	2	405.06	10547.52
34	2	1	4	4	2	3	1	2	406.63	10954.14
35	2	2	5	3	1	3	1	2	408.08	11362.23
36	2	1	5	3	2	2	1	2	409.38	11771.61
37	2	1	6	3	1	2	2	1	410.61	12182.21
38	2	1	7	2	1	2	1	2	411.79	12594.00
39	2	1	8	2	1	2	1	1	412.94	13006.94
40	1	1	8	2	1	2	1	1	414.00	13420.94
41	1	1	9	1	1	2	1	1	415.05	13835.98
42	1	1	10	1	1	1	1	1	416.08	14252.06
43	1	1	9	1	1	1	1	1	417.04	14669.09
44	1	1	9	1	1	1	1	1	417.97	15087.06
45	1	1	9	1	1	1	1	1	418.86	15505.91
46	1	1	9	1	1	1	1	1	419.70	15925.62

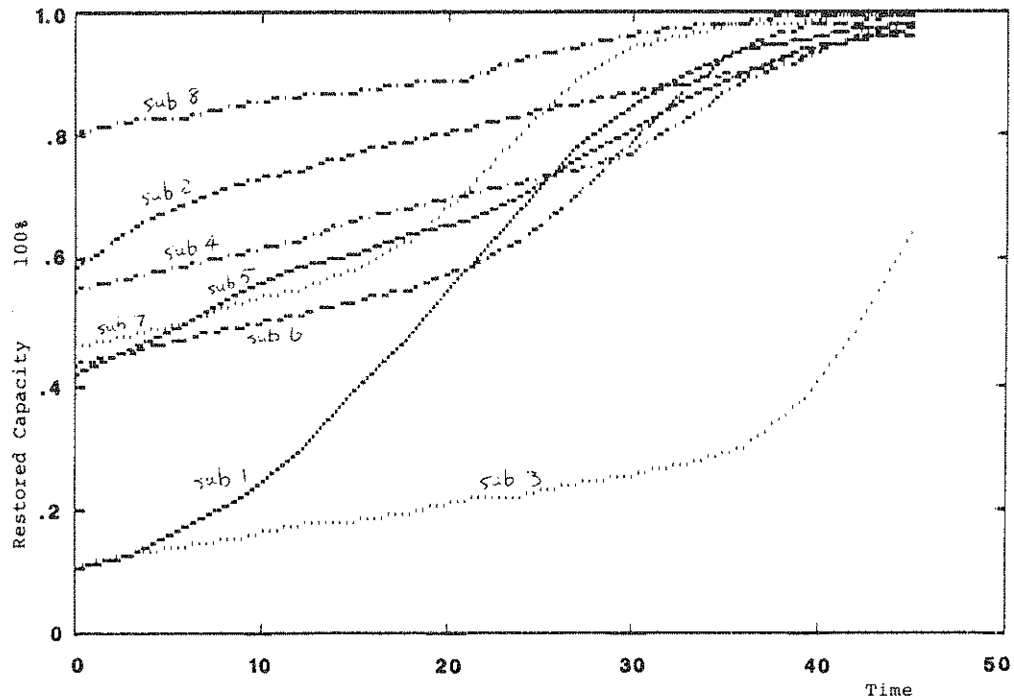

Figure 4-3 Restoration Curve of Lifeline for Case 2

4.2.3 Case 3

Parameters a_n and b_n in the transition rate formula (4-1) represent the geographical and structural characteristics of each subsystem, respectively. These parameters have tremendous influence on the restoration process of each subsystem, and then the optimal resource distribution. In order to check the influence of a_n and b_n, several scenarios were designed with changing values of a_n, and all other parameters fixed. Table 4-VIII shows the coefficients of transition rate probabilities for case 3. Table 4-IX is the optimal resource distribution in the new case. Figure 4-4 shows the dynamic evolution of each subsystem.

Table 4-VIII Coefficients of Transition Rate for Case 3

$a_1 = 0.1$	$a_2 = 0.2$	$a_3 = 0.3$	$a_4 = 0.4$	$a_5 = 0.5$	$a_6 = 0.6$	$a_7 = 0.7$	$a_8 = 0.8$

Table 4-IX Optimal Distribution of Resource Among the Subsystem N during Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	1	1	1	2	4	1	0	215.48	215.48
2	1	1	1	1	3	5	1	0	218.40	433.88
3	1	1	1	2	4	5	2	0	221.95	655.84

Table 4-IX Optimal Distribution of Resource Among the Subsystem N during Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
4	1	1	1	1	3	5	3	0	225.37	881.22
5	1	2	1	1	5	6	5	0	230.04	1111.26
6	1	3	1	2	6	7	7	0	235.95	1347.21
7	1	4	1	4	8	8	10	0	243.47	1590.67
8	1	4	1	3	7	9	11	0	251.29	1841.96
9	1	4	1	2	7	9	12	0	259.40	2101.36
10	1	3	1	2	6	10	12	1	267.66	2369.02
11	1	3	1	1	6	9	12	1	275.52	2644.54
12	1	3	1	1	5	9	12	1	282.98	2927.52
13	1	2	1	1	4	9	11	1	289.56	3217.08
14	1	3	1	1	5	8	10	1	295.57	3512.65
15	1	3	1	2	5	8	9	1	300.98	3813.64
16	1	3	1	2	4	8	7	1	305.46	4119.09
17	1	3	1	2	5	7	7	1	309.47	4428.55
18	1	3	1	2	5	6	5	1	312.74	4741.30
19	1	3	1	3	4	6	4	1	315.63	5056.93
20	1	4	1	3	5	5	3	1	318.29	5375.21
21	1	4	1	3	4	4	3	1	320.57	5695.78
22	1	4	1	3	4	4	2	1	322.63	6018.40
23	1	3	1	2	3	3	1	1	324.12	6342.52
24	1	5	4	5	5	4	2	1	326.54	6669.06
25	1	5	4	5	5	3	2	2	328.83	6997.89
26	1	5	4	5	4	3	2	5	331.16	7329.05
27	1	4	3	5	4	2	1	8	333.44	7662.48
28	1	3	1	4	2	1	1	12	335.67	7998.15
29	1	2	1	3	1	1	1	14	338.18	8336.33
30	1	1	1	1	1	1	1	6	339.77	8676.10
31	1	1	1	1	1	1	1	8	341.76	9017.86
32	1	1	1	1	1	1	1	12	344.44	9362.29
33	1	1	1	1	1	1	1	12	347.28	9709.57
34	1	1	1	1	1	1	1	12	350.23	10059.80
35	1	1	1	1	1	1	1	12	353.25	10413.05
36	1	1	1	1	1	1	1	11	356.16	10769.21
37	1	1	1	1	1	1	1	11	359.10	11128.31
38	1	1	1	1	1	1	1	11	362.04	11490.35
39	1	1	1	1	1	1	1	11	364.99	11855.34
40	1	1	1	1	1	1	1	10	367.75	12223.08
41	1	1	1	1	1	1	1	10	370.49	12593.57

Table 4-IX Optimal Distribution of Resource Among the Subsystem N during Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
42	1	1	1	1	1	1	1	10	373.18	12966.75
43	1	1	1	1	1	1	1	9	375.65	13342.39
44	1	1	1	1	1	1	1	9	378.05	13720.44
45	1	1	1	1	1	1	1	9	380.38	14100.81
46	1	1	1	1	1	1	1	9	382.61	14483.42

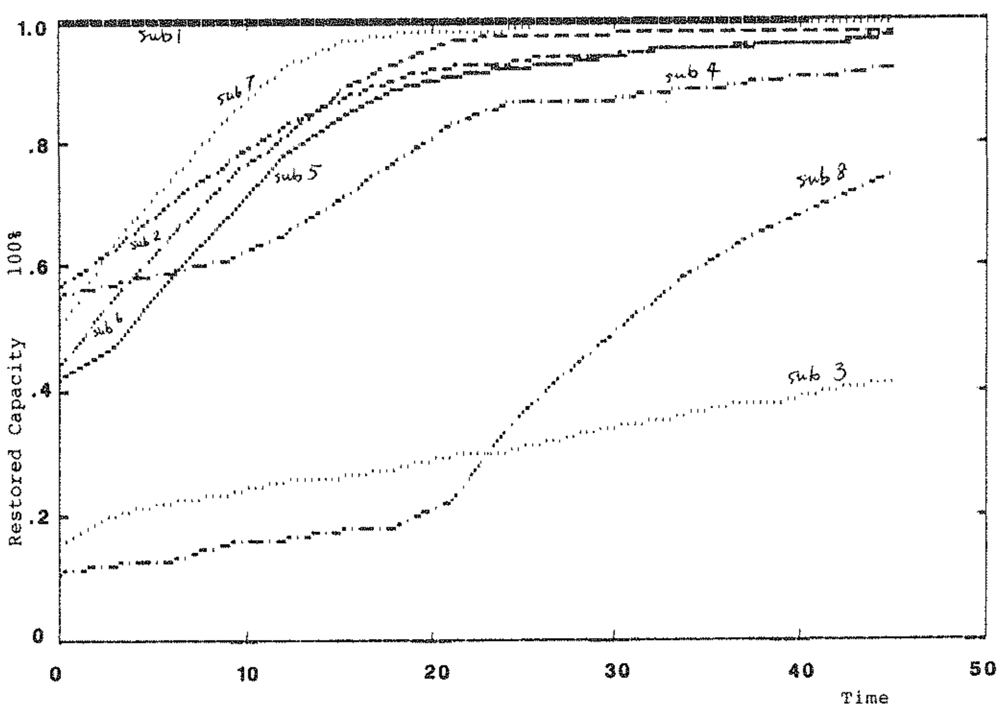

Figure 4-4 Restoration Curve of Lifeline in Case 3

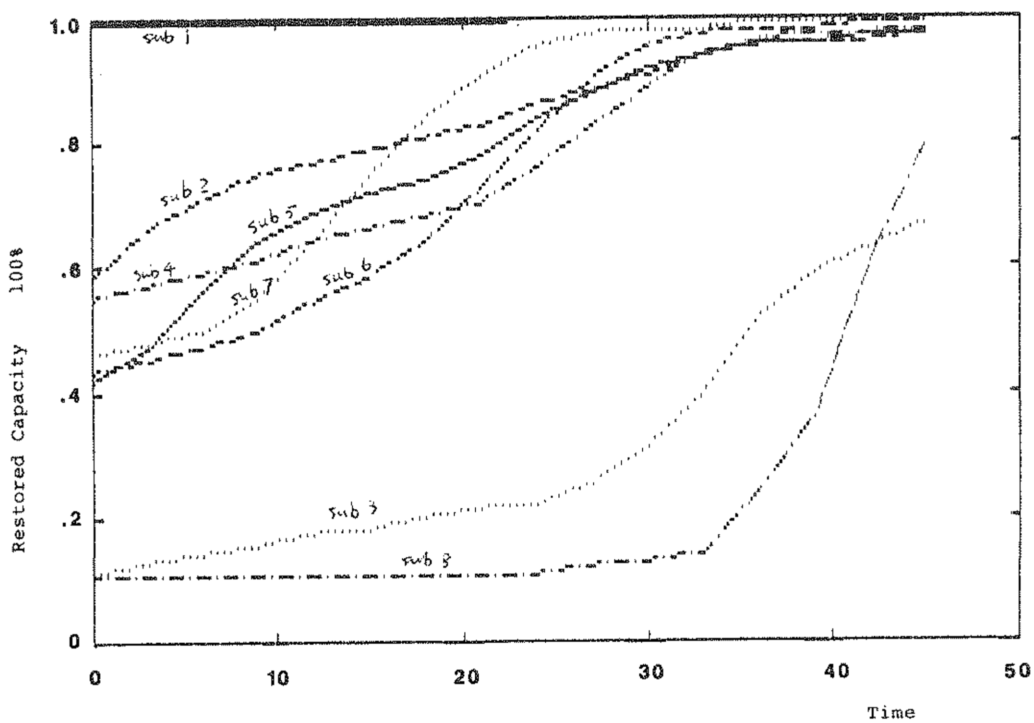

Figure 4-5 Restoration Curve of Lifeline in Case 4

4.2.4 Case 4

If the total available resources are fixed for the entire reconstruction period, the management authority should decide how to use the limited resource over the whole planning horizon. Generally speaking, there are three choices:

a. Distribute the resource evenly during the whole reconstruction period;
b. Allocate as many resources as possible to the damaged system during the earlier repair stage;
c. Increase resource supply after some time period.

At first glance, choice b seems most reasonable. But in reality, the management authority may choose alternative c. They will slow down the restoration process and wait for more outside aid [23]. Furthermore, the efficiency of resources employed during earlier repair periods may be less than that of later periods, due to insufficient information, poor planning and possible second events during earlier restoration periods.

Table 4-X is supposed resource supply planning for the entire repair period. In this case, the resource supply planning adopts choice c, and the resource supply will be increased gradually. Table 4-XI is the optimal resource distribution and total economic return for this case with the same parameters as case 1. Fig. 4-5 shows the influence of resource supply planning on the total optimal return.

Table 4-X Available Resource Supply for Each Repair Stage

11	11	11	11	11	11	11	11	12	12	12	12	13	13	13	13	14	14	15	15	15	21	21
23	24	25	26	27	28	30	30	30	30	30	33	36	36	36	36	36	36	36	36	36	36	36

Table 4-XI Optimal Distribution of Resource Among Subsystem N During Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	5	1	1	1	1	1	0	218.34	218.34
2	1	4	1	1	2	1	1	0	223.22	441.56
3	1	4	1	1	2	1	1	0	227.76	669.32
4	1	3	1	1	3	1	1	0	232.03	901.34
5	1	2	1	1	4	1	1	0	236.10	1137.44
6	1	2	1	1	4	1	1	0	240.03	1377.47
7	1	2	1	1	4	1	1	0	243.80	1621.27
8	1	2	1	1	4	1	1	0	247.40	1868.67
9	1	1	1	1	4	2	2	0	251.18	2119.85
10	1	1	1	1	3	2	3	0	254.90	2374.75
11	1	1	1	1	3	2	3	0	258.61	2633.36
12	1	1	1	1	2	2	4	0	262.35	2895.71
13	1	1	1	1	2	2	5	0	266.47	3162.17
14	1	1	1	1	1	2	6	0	270.67	3432.84
15	1	1	1	1	1	2	6	0	274.97	3707.82
16	1	1	1	1	1	2	6	0	279.31	3987.13
17	1	1	1	1	1	3	6	0	283.92	4271.04
18	1	1	1	1	1	3	6	0	288.44	4559.48
19	1	1	1	1	1	4	6	0	293.10	4852.58
20	1	1	1	1	1	4	6	0	297.57	5150.14
21	1	1	1	1	1	5	5	0	301.82	5451.96
22	1	1	1	1	4	6	7	0	307.17	5759.13
23	1	1	1	2	3	7	6	0	312.17	6071.30
24	1	1	1	3	4	8	5	0	317.19	6388.48
25	1	2	1	4	3	8	5	0	322.02	6710.50
26	1	2	1	4	3	9	4	1	326.65	7037.15
27	1	1	2	5	3	9	4	1	330.95	7368.10
28	1	2	3	5	3	9	3	1	335.01	7703.11
29	1	2	4	5	3	9	3	1	338.79	8041.89
30	1	2	5	6	3	9	3	1	342.34	8384.23
31	1	3	4	6	3	9	3	1	345.48	8729.71
32	1	2	6	6	3	8	3	1	348.24	9077.96

Table 4-XI Optimal Distribution of Resource Among Subsystem N During Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
33	1	2	7	6	3	8	2	1	350.67	9428.62
34	1	2	8	6	3	7	2	1	352.82	9781.45
35	1	2	9	5	3	6	2	5	354.92	10136.36
36	1	2	10	4	1	5	2	11	357.12	10493.48
37	1	1	9	2	1	4	1	17	359.64	10853.12
38	1	1	7	1	1	2	1	22	362.91	11216.03
39	1	1	5	1	1	1	1	25	367.05	11583.08
40	1	1	3	1	1	1	1	27	371.81	11954.89
41	1	1	3	1	1	1	1	27	376.85	12331.73
42	1	1	3	1	1	1	1	27	381.96	12713.69
43	1	1	3	1	1	1	1	27	387.04	13100.73
44	1	1	3	1	1	1	1	27	392.12	13492.85
45	1	1	3	1	1	1	1	27	397.21	13890.06
46	1	1	3	1	1	1	1	27	402.23	14292.29

4.2.5 Case 5

As we mentioned above, the one step transition rate formula plays an important role in this simulation. The proper choice of a transition rate formula will make the simulation more indicative of the real restoration process. A poorly chosen formula will lead to failure of this methodology. In the above simulation examples, an exponential formula was employed. In the present simulation case, the following transition rate formula is used.

$$ {}_{n}p_j(x) = \frac{a_n * X * (0.1*j)^{0.15}}{d + b_n * X} \qquad (4\text{-}2) $$

In formula (4-2), a_n and b_n have the same definition as in (4-1), and parameter d is a special term which makes the formula meet the requirement of a probability law.

Figure 4-6 shows the relation between transition rates and available resource for the exponential formula (4-1) and Figure 4-7 is for equation (4-2).

Table 4-XII is the simulation result for this case with same parameters as case 1.

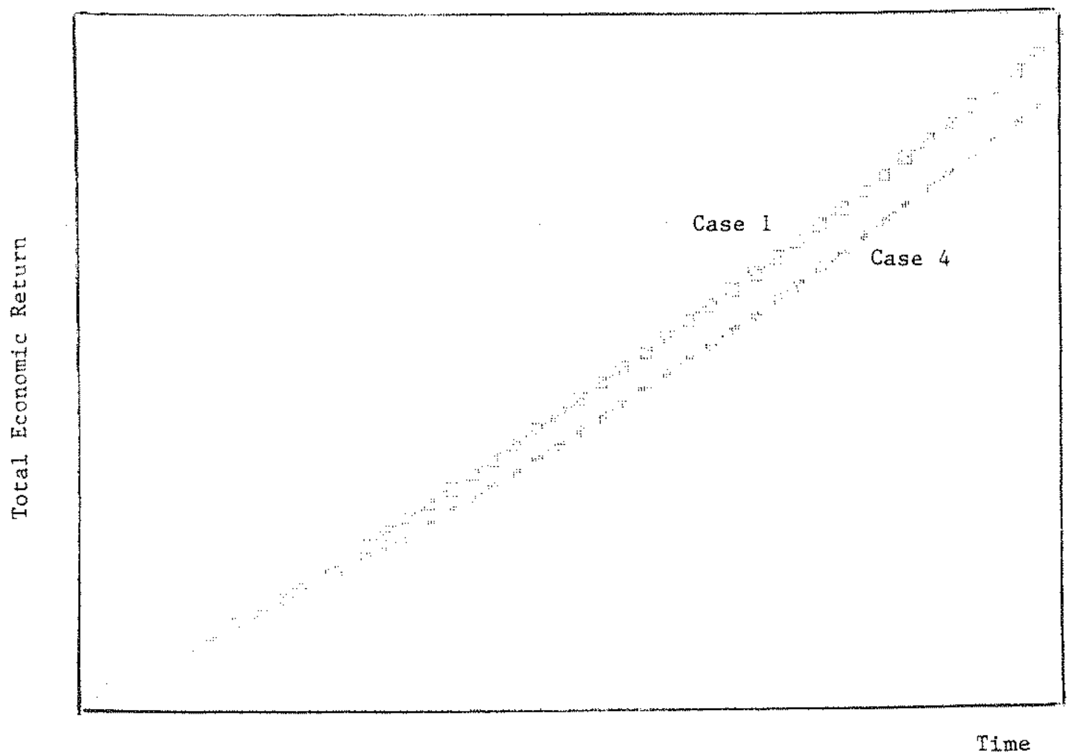

Figure 4-6 Comparison of Total Optimal Economic Return Between Case 1 and Case 4

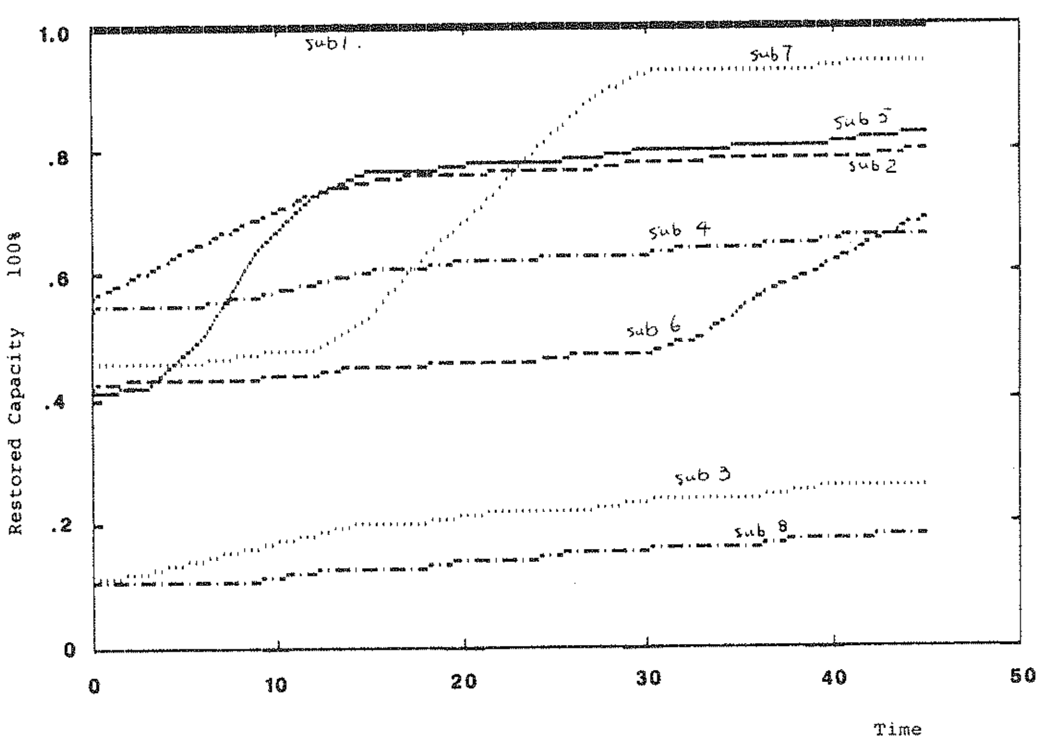

Figure 4-7 Restoration Curve of Lifeline in Case 5

Table 4-XII Optimal Distribution of Resource Among Subsystem N for Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	5	1	1	1	1	1	0	214.53	214.53
2	1	7	1	1	1	1	1	0	216.38	430.91
3	1	10	1	1	1	1	1	0	218.64	649.55
4	1	6	4	1	1	1	1	0	220.63	870.17
5	1	9	4	1	4	1	1	0	223.38	1093.55
6	1	8	3	1	12	1	1	0	226.82	1320.38
7	1	7	5	1	20	1	1	0	231.34	1551.71
8	1	7	1	1	23	1	1	1	235.67	1787.39
9	1	6	5	1	20	1	1	1	239.62	2027.01
10	1	8	4	1	19	1	1	1	243.27	2270.28
11	1	7	3	3	17	1	1	1	246.44	2516.72
12	1	7	4	5	13	1	1	1	249.30	2766.02
13	1	6	3	6	11	1	1	1	251.72	3017.75
14	1	7	5	5	9	1	1	1	253.99	3271.74
15	1	5	1	5	6	3	8	1	256.15	3527.89
16	1	1	1	1	1	4	17	1	258.14	3786.03
17	1	1	1	1	1	1	20	1	260.37	4046.39
18	1	1	1	1	1	1	17	1	262.57	4308.96
19	1	1	1	1	1	1	16	1	264.83	4573.79
20	1	1	1	1	1	1	16	1	267.22	4841.01
21	1	1	1	1	1	1	14	1	269.45	5110.46
22	1	1	1	1	1	1	13	1	271.60	5382.06
23	1	1	1	1	1	1	8	1	273.11	5655.16
24	1	1	1	1	1	1	20	1	276.14	5931.30
25	1	1	1	1	1	1	20	1	279.13	6210.44
26	1	1	1	1	1	1	22	1	282.24	6492.68
27	1	1	1	1	1	1	21	1	285.03	6777.71
28	1	1	1	1	1	1	18	1	287.30	7065.01
29	1	1	1	1	1	1	17	1	289.28	7354.29
30	1	1	1	1	1	1	6	1	290.18	7644.47
31	1	1	1	1	1	1	8	1	291.21	7935.68
32	1	1	1	1	1	4	9	1	292.50	8228.18
33	1	1	1	1	1	8	5	1	293.75	8521.93
34	1	1	1	1	1	11	2	1	294.99	8816.92
35	1	1	1	1	1	12	1	1	296.23	9113.15
36	1	1	1	1	1	11	1	1	297.42	9410.57
37	1	1	1	1	1	11	1	1	298.61	9709.18
38	1	1	1	1	1	11	1	1	299.81	10008.99

Table 4-XII Optimal Distribution of Resource Among Subsystem N for Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
39	1	1	1	1	1	11	1	1	301.03	10310.02
40	1	1	1	1	1	10	1	1	302.18	10612.20
41	1	1	1	1	1	10	1	1	303.35	10915.54
42	1	1	1	1	1	10	1	1	304.52	11220.06
43	1	1	1	1	1	9	1	1	305.63	11525.69
44	1	1	1	1	1	9	1	1	306.74	11832.43
45	1	1	1	1	1	9	1	1	307.86	12140.28
46	1	1	1	1	1	9	1	1	308.98	12449.27

SECTION 5
DISCUSSION AND POLICIES SELECTION

5.1 Simulation Analysis

In this simulation, five scenarios were examined, each with several cases. Comparing the simulation results, it can be seen how different factors affect the reconstruction process and the kinds of policies that should be adopted under the different situations.

The curve of evolution of subsystem 1 in case 1 experiences little change over time, because the initial probability state of subsystem 1 is nearly in the normal state. The subsystem 8 in the same case does not receive any resource at the beginning of the reconstruction process. At first glance, it appears unreasonable because the initial probability state vector is in a completely destroyed state. The emergency management authority would be expected to assign some rescue resource to the subsystem. But by carefully examining the economic return table, it can be seen that the economic return from functioning of subsystem 8 is very small. Since the criterion of optimizing the resource distribution is to maximize the total economic return from functioning of the entire lifeline system, subsystem 8 does not receive any rescue resource until other subsystems are nearly restored. Keep in mind that the subsystems are independent in this simulation. Dependence would introduce other considerations.

In case 2, the influence of initial damage probability on the reconstruction policy is checked. Compared with case 1, subsystem 8 receives some resources at the beginning of the restoration process. Although subsystem 1 is a completely destroyed state, it does receive rescue resources at the beginning of the restoration process. The result is different from subsystem 8 in case 1, where subsystem 8 does not receive any resource when it is in the totally destroyed state. From the return table, we see that subsystem 1 has a very high return even at lower states of capacity. This is why subsystem 1 receives rescue resource at lower capacity states.

In the transition rate formula, a_n and b_n are defined as geographical and structural characteristic parameters of the n-th subsystem, respectively. These two parameters will influence the transition rate dramatically. Comparing case 1 and 3, all final capacities in case 3 are reduced tremendously, because all a_n in case 3 are less than the corresponding values in case 1. The smaller the value a_n, the lower the final restored capacity. Consequently, the total expected return in case 3 is less than that of case 1, though the same amounts of resources were applied. Larger values of a_n, which may represent better geographical environments after the earthquake, may lead to higher restoration rates with fixed resources.

Case 1 and case 4 are compared to determine the influence of the resource supply policy on the restoration process. In both cases, the total available resources are the same for the entire planning horizon, but with different resource supply policies. In case 4, less resources were supplied to the earlier reconstruction process and more resources became available as the repair process evolved. Comparing the restoration processes of the two cases, the lifelines in case 1 were restored at a faster rate at earlier repair stages, though the final restored capacity is nearly the same for both cases. The total expected return in case 1 is a little higher than that in case 4. The lifelines in case 1 were restored to higher capacity in the earlier stage, and greater economic return was obtained. Therefore, it seems reasonable to supply as many resources as possible to the restoration process in the entire reconstruction period, assuming other considerations, such as waiting for outside aid, are neglected.

In case 5, a linear transition rate formula is used to replace the exponential formula. Both formulas have reasonable characteristics. In the linear formula, more resources are allocated to a damaged lifeline, so the restoration rate of the system is higher. But considering the restraint of "space," the restoration rate cannot be expected to increase without limitation. With the exponential formula, the restoration speed will grow at a lower increase rate when the resources increase. After the supplied resource grows beyond some level, saturation occurs and the restoration rate stays constant. Comparing Fig. 5-1 and Fig. 5-2 shows that the choice of the transition rate formula is so important that the formula will decide whether or not the simulation is applicable.

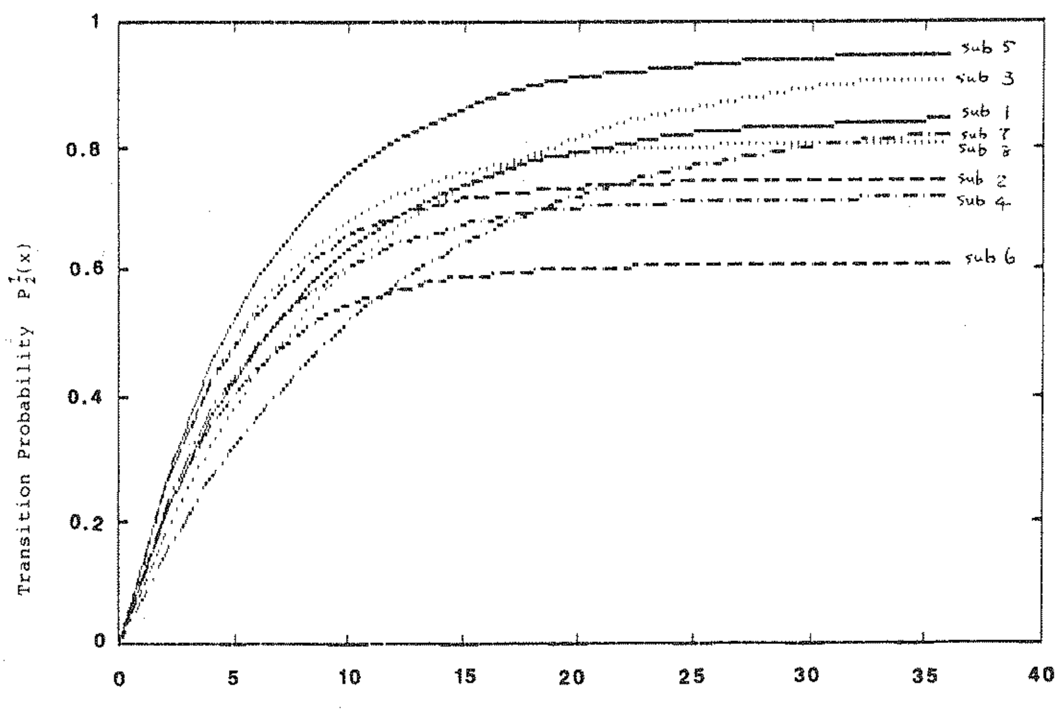

Figure 5-1 Exponential Transition Rate Curve

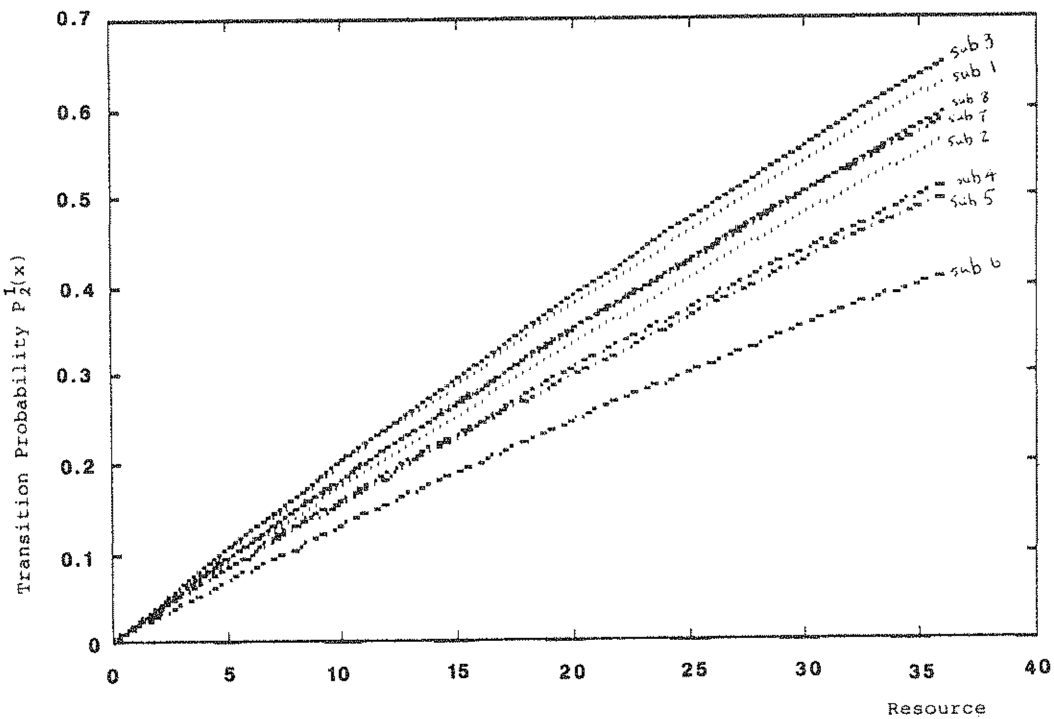

Figure 5-2 Linear Transition Rate Curve

5.2 Policy Recommendations

According to the simulation results, based on independent subsystems, the emergency management authority should assume the following descending priority for reconstruction policy. This assumes that the initial damage probability state and immediate economic return are the only two prevailing factors to influence the restoration processes.

a. Subsystems with higher economic return and lower damage probability state;
b. Subsystems with higher economic return and higher damage probability state;
c. Subsystems with lower economic return and lower damage probability state;
d. Subsystems with lower economic return and higher damage probability state.

The coefficient of a_n and b_n in the formula of transition rate represent the geographical and structural characteristics of a restored lifeline system, respectively. These two parameters influence the transition rate dramatically. Generally speaking, higher a_n and b_n leader to higher restoration rates. Therefore, the emergency management authority should assign higher priority to the subsystems with higher a_n and b_n.

SECTION 6
CONCLUSIONS

6.1 Summary

The objective of this research is twofold. First, is to extend the current state of knowledge in understanding the dynamic response of lifeline systems due to a catastrophic earthquake. Second, to recommend an optimal reconstruction strategy to the emergency management authority when mitigation and preparedness plans are developed. For the past twenty years, researchers have devised a number of methodologies to study the behavior of lifeline systems subject to earthquakes, statically or dynamically. Most, if not all, of these procedures do not study the problem of lifeline system response as a complete urban system. It is felt that the problem cannot be thoroughly understood without integrating the many disciplinary studies concerning earthquakes into a comprehensive view of the urban system.

The current investigation considers the lifeline system as a complex, multidimensional, stochastic and dynamic system during the period following the earthquake. Markov decision process is employed in this formulation.

6.2 Conclusions

The major results of this study are:

a. A theoretical formulation of seismic damage restoration processes for general independent lifeline systems is developed in terms of Markov chains. The optimal reconstruction policy is obtained according to the criterion of maximizing the expected economic return from the functioning of the lifeline system.

b. The methodology developed here can apply to general lifeline systems to estimate the time required for various capacity restorations. For example, in case 1, it is estimated that about 16 time periods are required for the 95% capacity restoration of subsystem 7.

c. By simulation, various scenarios are examined to determine the influence of different factors in the restoration process of lifeline systems. Initial damage probability states and immediate economic returns of lifeline systems are the two main factors in deciding reconstruction policy for an assumed probabilistic transition matrix.

6.3 Recommendations for Future Research

Future research directions are suggested below:

a. Accurate formulation of transition rate is critical for the validation of this model. Various possible functional forms should be investigated in order to choose the most suitable function to represent the realistic situation.

b. Interactions among subsystems are important factors which influence the restoration process of lifelines. Malfunction of subsystem i may delay the restoration process of subsystem j, or even make the restoration process of subsystem k impossible. In future studies, interactions among subsystems will be taken into account.

c. The determination of immediate economic return is so important that this model will fail without appropriate return data for each subsystem. Therefore, careful definition and collection of economic return data for each subsystem is a prerequisite to the application of this approach.

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Appendix

Computer Program for Simulation

```
C*********************************************************************
C*   THIS PROGRAM IS DESIGNED TO SIMULATE THE RECONSTRUCTION PROCESS *
C* OF A DAMAGED URBAN LIFELINE SYSTEM BY MEANS OF MARKOV MODEL. THE  *
C* OBJECTIVE OF THE SIMULATION IS TO FIND AN OPTIMAL ALLOCATION OF   *
C* LIMITED RECONSTRUCTION RESOURCES IN ORDER TO MAXIMIZE THE TOTAL   *
C* ECONOMIC RETURN FROM THE FUNCTIONING OF THE DAMAGED LIFELINE      *
C* SYSTEM.                                                           *
C*   TO RUN THIS PROGRAM, THE FOLLOWING DATA ARE NEEDED TO READ      *
C*     T--------THE TIME PERIOD OF SIMULATION;                       *
C*     SOU(I)---THE TOTAL AVAILABLE RESOURCE IN PERIOD I;            *
C*     N--------NUMBER OF LIFELINE SYSTEMS;                          *
C*     S--------NUMBER OF SUBAREAS IN THE STUDY REGION;              *
C*     R(I,J)---IMMEDIATE ECONOMIC RETURN OF I-TH LIFELINE AT J-TH   *
C*              CAPACITY(STATE);                                     *
C*     P(I,J)---INITIAL DAMAGE PROBABILITY OF I-TH LIFELINE AT J-TH  *
C*              STATE;                                               *
C*     A(I)-----GEOGRAPHICAL PARAMETER OF I-TH LIFELINE;             *
C*     B(I)-----STRUCTURAL PARAMETER OF I-TH LIFELINE.               *
C*                                                                   *
C*   TO CALCULATE                                                    *
C*     PROB(J,I,X)---PROBABILITY OF I-TH LIFELINE AT J-TH STATE WHEN *
C*                   X UNITS OF RESOURCE WAS ALLOCATED;              *
```

```
C*    D(I,X)--------THE OPTIMAL UNIT OF RESOURCE TO ALLOCATE TO I-TH *
C*                   LIFELINE WHEN ONLY LIFELINE I, I+1,..., N ARE   *
C*                   BEING CONSIDERED AND X-1 UNITS RESOURCE ARE     *
C*                   AVAILABLE;                                      *
C*    G(I,X)--------EXPECTED ECONOMIC RETURN OF I-TH LIFELINE WHEN   *
C*                   X UNITS OF RESOURCE ARE ALLOCATED;              *
C*    F(I,X)--------THE OPTIMAL RETURN FROM ALLOCATING (X-1) UNITS   *
C*                   OF RESOURCE IN LIFELINE I,I+1,...,N(I=1,2,..,N) *
C*                                                                   *
C*********************************************************************
C     MAIN PROGRAM
      DIMENSION F(8,101),R(8,10),A(8),P(8,10),Q(10,10),G(8,101),U(10,8,
     1101),B(8),EX(8,48),EIP(8),CAP(50,8),RET(50),TRET(50)
      INTEGER X,Z,SUM,XSTAR(8),Q,QP,D(8,101),Y,V,W,T,S,TM,SOU(46),TAR(8)
     2,DIST(50,8),TSOU,KK
      COMMON A,P,T,B,TM,V
      REAL CO,TRT
      READ(5,54) (SOU(I),I=1,46)
54    FORMAT(2(23I3/))
      READ(5,55)N,T,S,KK
55    FORMAT(4I6)
      READ(5,56) (A(I),I=1,8)
56    FORMAT(8F7.3)
      READ(5,58) (B(I),I=1,8)
58    FORMAT(8F7.3)
```

```
      READ(5,*) ((R(I,J),J=1,10),I=1,8)
      READ(5,*) ((P(I,J),J=1,10),I=1,8)
      TSOU=0
      DO 59 I=1,46
      TSOU=TSOU+SOU(I)
 9    CONTINUE
      WRITE(6,53) KK
 3    FORMAT(9X,'SIMULATION OF CASE',I4/)
      WRITE(6,60) N,S,TSOU
 0    FORMAT(3X,'THE NO.OF SUBAREA IS',I2,', THE NO.OF SYS.IS,',I2,' THE
     2 TOTAL AVAI.RESOU.DUR.RECON.PERIOD IS',I5/)
      WRITE(6,61) T
 1    FORMAT(' SUPPOSING',I3,' TIME OF PERIODS RECONSTRUCTION'/)
      WRITE(6,63) (A(I),I=1,8)
 3    FORMAT(' THE COE. OF A(I) IS  ',8F7.3)
      WRITE(6,69) (B(I),I=1,8)
 9    FORMAT(' THE COF. OF B(I) IS  ',8F7.3/)
      WRITE(6,66)
 6    FORMAT(5X,'  THE AVAILABLE RESOURCE AT EACH RECOVERY PERIOD'/)
      WRITE(6,71) (SOU(I),I=1,46)
71    FORMAT(23I3)
      WRITE(6,16)
16    FORMAT(/5X,' IMMEDIATE ECONOMIC RETURN TABLE'/)
      WRITE(6,68) ((R(I,J),J=1,10),I=1,8)
```

```
68    FORMAT(8(10F6.0/))
      DO 41 I=1,8
      EIP(I)=0.0
      DO 42 M=1,10
42    EIP(I)=EIP(I)+M*P(I,M)
41    CONTINUE
      WRITE(6,27) KK
27    FORMAT(10X,'SIMULATION RESULT OF CASE',I3/)
      WRITE(6,73)
73    FORMAT(5X,' PROB.OF.INI.STA.IN SUBAREA',24X,'EXP.CAPA.')
      WRITE(6,72)  ((P(I,J),J=1,10),EIP(I),I=1,8)
72    FORMAT(8(10F6.1,F8.2/))
      TRT=0.0
      DO 1000 TM=1,T
      K=SOU(TM)+1
      DO 201 N=1,8
      DO 202 X=1,K
      EX(N,X)=0.0
      DO 203 M=1,10
      U(M,N,X)=PROB(M,N,X)
      EX(N,X)=EX(N,X)+M*U(M,N,X)
203   CONTINUE
      WRITE(6,25) N,X,TM
25    FORMAT(' SYS.PROB.OF',I2,'TH SUBSYS.WITH',I3,' UNIT RESO. AFTER
```

```
     2PERIOD',I2/)
      WRITE(6,75) (U(M,N,X),M=1,10),EX(N,X)
75    FORMAT(11F7.4/)
202   CONTINUE
201   CONTINUE
      DO 110 N=1,8
      G(N,1)=0
110   CONTINUE
      DO 120 N=1,8
      DO 130 X=2,K
      G(N,X)=0
      DO 140 M=1,10
      G(N,X)=G(N,X)+U(M,N,X)*R(N,M)
140   CONTINUE
130   CONTINUE
120   CONTINUE
      DO 129 N=1,8
      DO 129 X=2,K
      IF ((EX(N,X)-10.0).LE.0.0) GO TO 129
      G(N,X)=0.0
129   CONTINUE
      WRITE(6,173)
173   FORMAT(/5X,'THE TABLE OF EXPECTED RETURN'/)
      WRITE(6,*)((G(I,X),X=1,K),I=1,8)
```

```
C77   FORMAT(8(20F7.2/))
      KP1=K
      DO 11 X=1,KP1
      N=8
      F(N,X)=G(N,X)
      D(N,X)=(X-1)
11    CONTINUE
      I=N-1
3     X=1
      F(I,X)=G(I,1)+F(I+1,1)
      D(I,X)=0
      DO 5 X=2,KP1
      F(I,X)=G(I,1)+F(I+1,X)
      D(I,X)=0
      DO 5 Z=2,X
      IF (G(I,Z)+F(I+1,X-Z+1).LE.F(I,X)) GO TO 5
      F(I,X)=G(I,Z)+F(I+1,X-Z+1)
      D(I,X)=(Z-1)
5     CONTINUE
      IF (I.EQ.1) GO TO 6
      I=I-1
      GO TO 3
6     XSTAR(1)=D(1,KP1)
      DO 8 I=2,N
```

```
      SUM=0
      IMI=I-1
      DO 7 J=1,IMI
      SUM=SUM+XSTAR(J)
      XSTAR(I)=D(I,KP1-SUM)
      CONTINUE
      DO 601 I=1,8
      TAR(I)=XSTAR(I)+1
      DO 601 M=1,10
      P(I,M)=U(M,I,TAR(I))
01    CONTINUE
      WRITE(6,37) TM
7     FORMAT(/5X,'OPT.RET.ALLO.(X-1) UNIT OF RES.TO SYS.DUR.PERI.',I3/)
      WRITE(6,*)((F(I,J),J=1,K),I=1,8)
8     FORMAT(8(36F7.2/))
      WRITE(6,102) TM,F(1,KP1)
02    FORMAT(/' THE OPT.RETU. DURING PERIOD',I3,' IS',F10.3/)
      RET(TM)=F(1,KP1)
      TRET(TM)=TRT+RET(TM)
      TRT=TRET(TM)
      WRITE(6,103) (I,I=1,8)
03    FORMAT(1X,' THE OPT.ALLO. IN SUB.',8I7/)
      WRITE(6,104) (XSTAR(I),I=1,8)
04    FORMAT(23X,8I7)
```

```
      WRITE(6,106) TM
106   FORMAT(/' THE CUR.EXP.CAPA.OF SYS. AFTER TIME',I4/)
      WRITE(6,308) (EX(I,TAR(I)),I=1,8)
308   FORMAT(8F9.2/)
      DO 310 I=1,8
      CAP(TM,I)=EX(I,TAR(I))
      DIST(TM,I)=XSTAR(I)
310   CONTINUE
1000  CONTINUE
      WRITE(6,331)
331   FORMAT(6X,'THE OPT. DIST. OF RESOURCE'/)
      WRITE(6,333) (I,I=1,8)
333   FORMAT(' T\N ',8I5,3X,'OPT.RET. ACCU.RET.OF T PER.')
      WRITE(6,335) (T,(DIST(T,I),I=1,8),RET(T),TRET(T),T=1,46)
335   FORMAT(I3,2X,8I5,F10.2,F13.2)
      WRITE(6,337)
337   FORMAT(/)
      WRITE(6,312) (T,(CAP(T,I),I=1,8),T=1,46)
312   FORMAT(I3,2X,8F6.2)
      STOP
      END
C     SUBROUTIN
      REAL FUNCTION PROB(W,Y,V)
      DIMENSION A(8),Q(10,10),B(8),P(8,10)
```

```
      INTEGER W,Y,I,J,L,T,TM,VI,V
      REAL O
      COMMON A,P,T,B,TM
      DO 3 I=1,10
      DO 5 J=1,10
      IF (J-I) 40,50,60
0     Q(I,J)=0
      GO TO 5
0     IF(I.LT.10) GO TO 15
      Q(I,J)=1
      GO TO 6
5     S=V-1
      O=I
      Q(I,J)=1-(A(Y)*(1-1/EXP(((0.01*O)**0.15)*B(Y)*S)))
      GO TO 5
0     IF(J-I-1) 70,80,90
0     GO TO 5
0     S=V-1
      O=I
      Q(I,J)=A(Y)*(1-1/EXP(((0.01*O)**0.15)*B(Y)*S))
      GO TO 5
0     Q(I,J)=0
5     CONTINUE
3     CONTINUE
```

```
 6      IF (W.GT.1) GO TO 99
        IF (TM.NE.6) GO TO 99
        VI=V-1
        WRITE(6,81) Y,VI
81      FORMAT(5X,'TRAN.MATRIX IN SUBSYS.',I3,'  WITH RESOURCE',I4)
        WRITE(6,91)((Q(I,J),J=1,10),I=1,10)
91      FORMAT(/10(10F7.4/))
99      PROB=0
        DO 685 L=1,10
685     PROB=PROB+P(Y,L)*Q(L,W)
400     RETURN
        END
```

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NATIONAL CENTER FOR EARTHQUAKE
ENGINEERING RESEARCH

State University of New York at Buffalo

SYSTEMS STUDY OF URBAN RESPONSE AND RECONSTRUCTION DUE TO CATASTROPHIC EARTHQUAKES

by

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PREFACE

The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

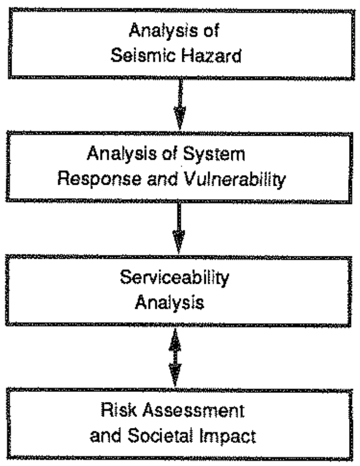
This technical report pertains to Program 3, Lifeline Systems, and more specifically to water delivery systems.

The safe and serviceable operation of lifeline systems such as gas, electricity, oil, water, communication and transportation networks, immediately after a severe earthquake, is of crucial importance to the welfare of the general public, and to the mitigation of seismic hazards upon society at large. The long-term goals of the lifeline study are to evaluate the seismic performance of lifeline systems in general, and to recommend measures for mitigating the societal risk arising from their failures.

From this point of view, Center researchers are concentrating on the study of specific existing lifeline systems, such as water delivery and crude oil transmission systems. The water delivery system study consists of two parts. The first studies the seismic performance of water delivery systems on the west coast, while the second addresses itself to the seismic performance of the water delivery system in Memphis, Tennessee. For both systems, post-earthquake fire fighting capabilities will be considered as a measure of seismic performance.

The components of the water delivery system study are shown in the accompanying figure.

Program Elements:



Tasks:

Wave Propagation, Fault Crossing
Liquefaction and Large Deformation
Above- and Under-ground Structure Interaction
Spatial Variability of Ground Motion

Soil-Structure Interaction, Pipe Response Analysis
Statistics of Repair/Damage
Post-Earthquake Data Gathering Procedure
Leakage Tests, Centrifuge Tests for Pipes

Post-Earthquake Firefighting Capability
System Reliability
Computer Code Development and Upgrading
Verification of Analytical Results

Mathematical Modeling
Socio-Economic Impact

Risk assessment and societal impact studies are an integral part of the lifeline systems program. Risk arising from lifeline system failures due to seismic action and its impact on society must be assessed. Measures for mitigating such an impact must be developed by engineers and scientists when they pertain to technical issues or by socio-economic experts when they relate to societal issues. In this way, the lifeline systems' response to a major earthquake, and the interactions among various subsystems can be better understood, thus providing knowledge that is useful in earthquake mitigation and preparedness planning. Some of these tasks are suitable for incorporation into expert systems for the management of lifelines in emergencies.

This technical report addresses itself to the issue of how lifeline systems damaged by earthquakes can be effectively restored under limited reconstruction resources. Such a restoration condition is an important component of the overall strategy for mitigating the societal impact of disasterous earthquakes.

ABSTRACT

The functioning of lifeline systems after a major earthquake is critical to the modern urban center. The system study of lifelines response to catastrophic earthquakes is the essential prerequisite step for the emergency management authority to form a mitigation and reconstruction plan in order to minimize the total loss caused by the earthquake.

This study develops an applied formulation of lifeline restoration processes in the post earthquake period by the method of Markov decision process. The objective of this research is to test various reconstruction strategies to determine optimal mitigation policies based upon various reconstruction goals, in particular, to optimize the distribution of limited reconstruction resources. By computer simulation, various scenarios are examined and useful information that is important to the emergency management authority is obtained.

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SECTION 1
INTRODUCTION

1.1 Overview

Potentially catastrophic earthquakes occur often in many parts of the world. During the past 80 years, about 10 earthquakes with Richter magnitude 7.0 or larger occurred per year in the world. In each event, the casualties vary from hundreds to thousands and property damage can range from millions to billions of dollars. In the United States, 42 of the 50 states have experienced perceptible earthquake shaking in the past. During 1982, 70 earthquakes with Richter magnitude greater than 5.0 were recorded in the United States. On the average, by survey of historical statistics, a disastrous earthquake, one with Richter magnitude 8.0 or more, occurs in America once every twelve years.

Although southern California is regarded as a high risk seismic area in the United States, and New England is not generally considered as an area of seismic risk by the public, the likelihood of a major earthquake occurring in New England does exist. Based on statistics of historical data and geological observation, geologists unanimously agree on the inevitability of major earthquakes in California and New England, as well as the New York area, with Richter magnitude of 7.0 and larger. Because about 50% of the Nation's total population and resources are located around these likely earthquake zones, casualties could be high and property damage could total as much as $10 billion. Therefore, the U.S. has to treat this problem seriously.

Although a disastrous earthquake, generally speaking, is not controllable, adequate preparedness and proper response strategy to deal with such an event can dramatically reduce the casualties and property damage, according to the experience in the United States and other countries. Therefore, it is desirable to formulate and analyze the possible behaviors (states) of an urban system during and after a major earthquake, in order to devise preparedness and response plans for coping with potential disaster.

Past experience in major earthquakes shows us that much of the damage in a seismic event may be caused not only by the direct effect of earthquake shocks, but also by secondary events such as fire, gas explosion, toxic spill, interruption of transportation and communication, dam collapse and flooding. Fortunately, the secondary events are more controllable than the direct earthquake excitation. Although some suggestions were put forward to reduce the magnitude of a potential earthquake, such as releasing the energy of a potential earthquake gradually by some artificial method, no engineering method appears to be available in the near future. In contrast to the shock wave, the secondary events can be controlled, at least to some extent, if we fully understand the behavior of the system during and after a major earthquake.

Among all the factors influencing casualties and property damage, we are most interested in the behavior and dynamic response of lifeline systems in the urban areas subject to earthquake shocks. "Lifeline" is a general term denoting all networks and systems necessary for the sustenance of human life and well-being. It covers pipelines of all kinds, transportation networks, communication and power networks, health and hospital services, critical structures, etc. Because modern society is increasingly dependent on lifeline systems, especially in the urban center, the functioning of these systems in a post-earthquake environment is critical. Therefore, many aspects of earthquake and earthquake-caused damage to lifelines have been the subject of intensive research in recent years. While much work has been done to evaluate the dynamic response of lifelines to earthquakes, they have not been treated in general as a totally integrated urban system. For instance, mitigation polices for buildings and structures may influence the ability of an area's transportation and communication networks to remain functional. A holistic view of the situation, however, might provide insight into whether mitigation polices for strengthening structures, or provisions for establishing alternative emergency patterns of transportation and communication will prove most beneficial for reducing losses due to an earthquake. Additionally, the emergency management authority should have some priority list for the consideration of limited resources and the order of importance of subsystems when they develop a response plan.

Several factors make the evaluation of the dynamic response of lifelines to earthquakes very difficult. The dynamic response of a lifeline system to a major earthquake is a complicated process encompassing many variables such as earthquake magnitude and duration; population density and distribution characteristics; land-use patterns and construction techniques; geological configuration; vulnerability of other lifeline systems; complex response operations; and long-term physical, social and economic recovery policies.

1.2 Lifeline Earthquake Engineering

Lifeline earthquake engineering has been an intensive research field since the 1971 San Fernando earthquake. Considering that modern urban areas have been and are still growing day by day, and human activities are more dependent on lifeline systems than ever before, the understanding of the dynamic response of lifeline systems to a major earthquake becomes very important. Urban areas are very sensitive to the loss of service of lifelines under seismic hazard.

A brief review of past research work in the field will be helpful to establish the advances made in this study and identify actions which can now be taken to advance the current knowledge in the area. The past research work in the field can be classified in the following categories.

1.2.1 Discrete Event Simulation Method

The main objective of this approach is developing a methodology to evaluate lifeline system performance during large earthquakes in major metropolitan areas. The general approach to lifeline vulnerability analysis is through the integrated use of deterministic models, Monte Carlo methods and discrete event simulation on digital computer.

Schiff [9] chose an electric transmission system in an urban center as a case study. The simulation began with the choice of a particular hypothesized earthquake. The severity of ground motion is found at each site where lifeline facilities are located, and damage degree of equipment at each site is determined by some attenuation law - the relationship between damage probability of system and earthquake intensity. The local seismic environment is also used to estimate the reduction in power demand, due to damage, by customers. Post-earthquake recovery operations are simulated day-by-day until full recovery is achieved under emergency operation conditions. Results of the simulation include identification of which equipment had to be repaired, man-hours and other resources required, and customers' service statistics for each day. Several experiments assessed the basic seismic response of the system and affects of random variation in equipment damages, repair times and travel times. Sensitivity analysis was performed, examining variations in post-earthquake demand reduction, spare transformer availability, loss of generality capacity, increased seismic resistance of certain equipment and priorities for assigning repair crews.

The logical structure of the power system simulation is shown in Fig. 1-1 [9].

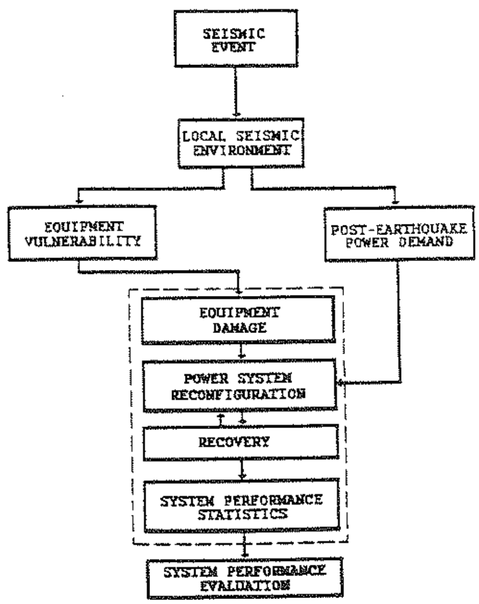

Figure 1-1 Logical Structure of Power System Simulation

1.2.2 Failure Probability Analysis

In the probability and network analysis method [8], the researchers are mainly interested in finding the failure probability of lifeline systems under a given earthquake. In the analysis, the lifeline system is treated as a network consisting of nodes (sources, distribution center, pumping stations, etc.) and links (transportation or communication lines, roads and pipelines, etc.). In contrast to buildings and structures, lifeline networks are usually continuously distributed over a sizable geographic area. Therefore, the various parts of the system will undergo different levels of shock due to any given earthquake. This fact suggests that a different approach from that of the case of buildings and structures should be used. One such approach is finding the probability of the network failure. However, the term "failure" might mean different things to different people in different situations. Therefore, failure can have a useful meaning only if it is expressed in reference to a given level of network performance. Failure of network performance usually will be defined as falling below the least acceptable level of service.

Using an assumed attenuation law for a given earthquake, it is relatively simple to find the failure probability of a component of a network, or a basis network system (system in series or in parallel, each consisting of a single input and a single output). For a more complex network, the task of finding the probability of network failure becomes more complex. These difficulties also increase as the requirement of the least acceptable level of network performance (objective) becomes more demanding and stringent. Therefore, it will be beneficial if any given network can be transformed into an equivalent simple network. It is demonstrated that any given network with a set of performance requirements can be transformed into another network with a single input-output pair, and the only requirement is the ability to go from input to output of the equivalent network [8]. The only basic network of special interest to the present work is a network of series systems in parallel (SSP) with a certain number of tie-sets (NT). Then, the following problem is addressed: find the probability that at least q out of NT fail simultaneously due to threats from a given set of sources in areas with known histories of earthquakes, where q is related to the least acceptable performance. A case study is shown in Fig. 1-2 [8].

In order to assess damage probability required to study the network failure statistics, probability damage matrices as defined in [26] have been applied. These damage matrices are often a consensus of best guesses by panels of experts, based upon past experience and observations in a given urban area.

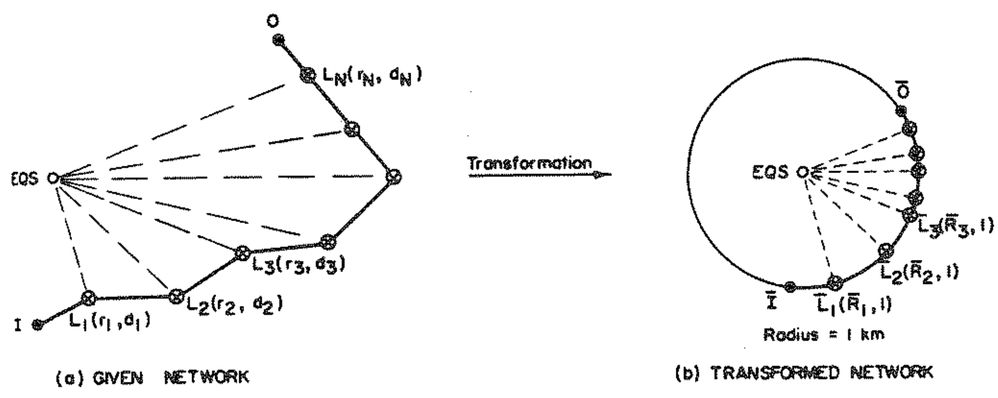

Figure 1-2 Topographical Transformation of a Discrete Basic Network in Series

1.2.3 Minimum Tree Method

R. Isoyama et al. [22] developed a practical method for simulating the post-earthquake restoration process of a city gas supply system. The restoration process of a middle-pressure gas network is simulated by using the concept of a minimum tree of network theory, which determines the restoration order under a given strategy.

The order of priority for restoration of the middle-pressure pipeline (called link) is determined by making a global judgement about the nodes (district regulators). The technique making use of the network theory is proposed for examining the factors of various kinds related to the determination of the order of priority of the restoration process. The factors related to the link are given to each link in term of link distance, and used to obtain the shortest route from each node to the source (gas plant). Furthermore, the weight of the link is calculated by superposing the node factors, in the form of weight, to the said shortest route. The order of priority for restoration of the link is determined from the magnitude of the link weight.

After the favorable routes from every demand node to a source on the network are determined, the higher the frequency of use of a given link, as a favorable route for accessing many demand nodes, the higher the degree of priority of the link in question.

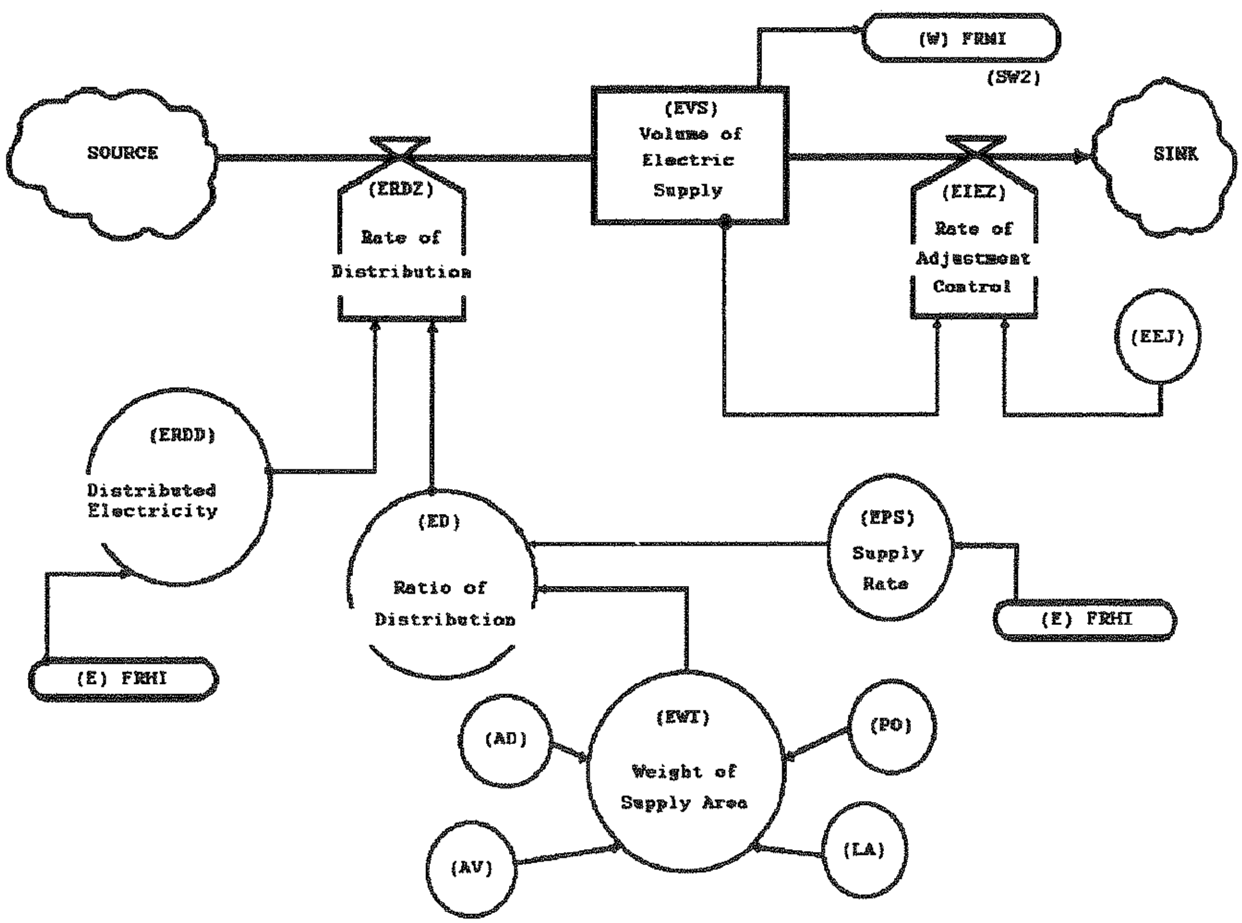

Figure 1-3 Functional Restoration Model for Power Supply System

1.2.4 System Dynamics Method

Hoshiya et al. [20] presented a system dynamics model to evaluate lifeline performance after an earthquake for a water supply network and an electric power supply network. By this model, if the initial state of damage distribution of both systems due to earthquake is given, and if the restoration strategy during post-earthquake recovery period is specified, the lifeline performance is simulated in terms of percentages of the corresponding normal supply of water or electricity supply quantity.

The main features of this performance evaluation model are illustrated in Fig. 1-3 [20], where each main flow consists of levels and their controlling values. By this model, it is possible to forecast the state of functional restoration of electric power and water supply system.

1.2.5 Objective Optimization Method

In papers by Jacobsen and Shinozuka, [15, 21] optimization problems dealing with water transmission and distribution systems have been studied. In Jacobsen's paper, the water distribution network synthesis problem can be described as follows: given various water supply locations and various water demand locations, the problem is to choose an optimal way to connect supply and demand locations, considering the potential seismic risk. The word "optimal" refers to minimizing construction costs plus discounted future earthquake damage costs subject to constraints which require that water demands, at various locations, be satisfied. Computed with the above approaches, which focus on "failure" or "success," this method is mainly concerned with future damage cost to the system and how changes in system design affect future damage costs, as well as initial construction costs. In particular, the goal of the research is to develop a means of calculating, in advance, future damage costs due to earthquakes, and the design of the system. Such information, together with initial construction costs, provides the means by which an optimal network can be designed.

1.2.6 Probability Importance

Yamada, et al, [19] developed a methodology to prepare rational countermeasures for seismic damage to lifeline systems, based on concepts of probabilistic importance. Probabilistic importance is defined as the rate at which system reliability improves as the reliability of the i-th link improves. This importance is expressed as follows;

$$I_i(t) = \frac{\partial g\,(q_i(t))}{\partial q_i(t)} \tag{1-1}$$

where g and q_i represent the unreliabilities of the system and the i-th link, respectively. $I_i(t)$ is the probability that the system is in a state at time t in which the functioning of the i-th link is critical; i.e., the system functions and fails when the i-th link functions and fails, respectively.

Based on this concept, various measures are applied to evaluate importance ranking of lifeline system components and cut sets in fault trees. Then, the importance order of the lifeline system components can be used to determine the restoration priority during the post-earthquake reconstruction process.

1.2.7 Markov Transition Model

Hoshiya [20] developed a theoretical formulation of lifeline restoration processes to evaluate a lifeline's functional performance in the post-earthquake period on the basis of a discrete-state discrete-transition Markov process. Given a fixed transition rate value, this model can evaluate the time required to restore the damaged lifeline system to some specific state or capacity. An underground water pipeline system in the city of Tokyo is chosen as a case study. The macroscopic system performance was evaluated in terms of the expectation of the restoration as a function of time.

1.3 Objective of this Investigation

The objective of this study is to understand the lifeline system's response to a major earthquake, the interactions among various subsystems, and by so doing, provide knowledge that could be useful in earthquake mitigation and preparedness planning. Previous studies in lifeline earthquake engineering have centered on the following problems: [2, 3, 4]

a. Identification of hazard prone system components;
b. Evaluation of lifeline performance after earthquakes;
c. Determination of restoration order of lifeline components;
d. Optimization of some system variables such as maximizing the total recovery area in given time limit.

While much effort has been applied to evaluate the dynamic response of lifelines to earthquakes, we note that the overall problem of lifeline system response has apparently not been studied as a complete urban system. For instance, mitigation policies for buildings and structures may influence the ability of the area's transportation and communication networks to remain functional. A holistic view of the situation, however, might provide insight into whether mitigation policies for strengthening structures, or provisions for establishing alternative emergency patterns of transportation and communication will prove most beneficial for reducing losses due to an earthquake. Besides, failure of some lifelines in certain sub-areas may only cause inconvenience, but the complete failure of the lifeline in the entire system will bring about disaster. For instance, if a water system only fails in some districts, the people in those areas can get water from adjacent districts. But if the system fails completely or fails in most areas, the supply of potable water rapidly becomes insufficient for sustaining needs. Furthermore, the emergency management authority should have some priority list for the consideration of limited resources and the importance order of the subsystems when they construct a response plan.

It is not possible to understand the impacts of mitigation and preparedness strategies without integrating the many disciplinary studies concerning earthquakes into a comprehensive view of the situation. This investigation considers the lifeline system as a complex, multidimensional, stochastic and dynamic system during the reconstruction period following a major earthquake. The analysis includes examination of dynamic capacity evolution of multiple lifeline systems, and the factors affecting the evolution process. In particular, we develop a general methodology to evaluate the restoration process of the lifeline system in the post-earthquake period. The goal of the method is to optimize the distribution of limited reconstruction resources, including materials and man-power, and to maximize the total economic return from the functioning of the repaired lifeline system. Markov decision process is used as the main tool, and an urban model technique based on a spatial economic model is also employed to represent the spatial distribution of lifeline capacity among the distinct subsystems.

SECTION 2
METHODOLOGY

2.1 Markov Decision Process

2.1.1 Markov Process and Markov Chain

A Markov process is a stochastic process with Markovian memoryless property. Let (X_t $t \geq 0$) be a discrete random process with state space $S_x = \{0, 1, 2,...\}$. Consider

$$0 < t_1 < t_2 < t_3 < t_4... < t_n$$

and

$$P\{X_{tn} = k_n \mid X_{tn-1} = k_{n-1} \;,..., X_{t1} = k_1\} \tag{2-1}$$

where k_j, j = 1, 2..., n are any nonnegative integers. If for all such t_j and k_j we have

$$P\{X_{tn} = k_n \mid X_{tn-1} = k_{n-1},..., X_{t1} = k_1\} = P\{X_{tn} = k_n \mid X_{tn-1} = k_{n-1}\} \tag{2-2}$$

then the sequence $\{X_t,\ t\ 0\}$ is called a Markov process. Equation (2-2) defines the Markov property. The distinguishing feature expressed by (2-2) is that the future value of X_{tn} only depends on the last known value of X_t, namely X_{tn-1}, and is independent of all previous values.

A Markov chain is a Markov process with discrete state space, and the Chapman-Kolmogorov equation for a Markov chain takes the following form for any times s > t > u ≥ 0 and states j and k:

$$p_{jk}(u, s) = \sum_i p_{ji}(u, t) * p_{ik}(t, s) \tag{2-3}$$

where "*" denotes multiplication and p_{jk} (u, s) is the probability of moving from state j to k in time beginning at u and ending at s, and the summation is over all states of the chain. The basic concept of the Markov chain are those of "state" of a system and state "transition." To study Markov chains, we must specify the probabilistic nature of the state transition. It is convenient to assume that the time between transition is a constant. Suppose that there are N states in the system numbered from 1 to N. If the system is a simple Markov process, then the probability of a transition to state j during the next time interval, given that the system occupies state i, is a function only of i and j and not of any history of the system before its arrival in i. In other words, we may specify a set of conditional probabilities p_{ij} that a system which now occupies state i will occupy state j after its next transition. Since the system must be in some state after its next transition, then

$$\sum_{j=1}^{N} p_{ij} = 1 \qquad i = 1, 2, ..., N$$

where the probability that the system will remain in i, p_{ii}, has been included. Since the p are probabilities,

$$0 \leq p_{ij} \leq 1$$

Considering all iεN, we have the following transition matrix

$$P = \begin{vmatrix} p_{11} & p_{12} & \cdots\cdots & p_{1,N-1} & p_{1N} \\ p_{21} & p_{22} & \cdots\cdots & p_{2,N-1} & p_{2N} \\ & & \cdots\cdots & & \\ p_{N-1,i} & p_{N-1,2} & \cdots & p_{N-1,N-1} & p_{N-1,N} \\ p_{N1} & p_{N2} & \cdots & p_{N,N-1} & p_{NN} \end{vmatrix} \qquad (2\text{-}3)$$

The transition matrix P is thus a complete description of the stationary Markov chain. We make use of this matrix to answer all questions about the process. For instance, we may wish to know the probability that a system will be in state i after n time periods if we know the system is in state j at the beginning of the n time period. To answer this and other questions, we define a state probability $p_i(n)$, the probability that the system will occupy state i after n transitions if its state at n=0 is known. It follows that

$$\sum_{i=1}^{N} p_i\ (n) = 1 \qquad (2\text{-}4)$$

$$p_j\ (n+1) = \sum_{i=1}^{N} p_i\,(n) * p_{ij} \qquad n = 0, 1, 2,... \qquad (2\text{-}5)$$

If we define a row vector of state probabilities $\overline{p}\,(n)$ with components $p_i(n)$, then

$$\overline{p}\,(n+1) = \overline{p}\,(n) * P \qquad n = 0, 1, 2,... \qquad (2\text{-}6)$$

Since by recursion we have have

$$\begin{aligned} \overline{p}\,(1) &= \overline{p}\,(0) * P \\ \overline{p}\,(2) &= \overline{p}\,(1) * P = \overline{p}\,(0) * P^2 \\ \overline{p}\,(3) &= \overline{p}\,(2) * P = \overline{p}\,(0) * P^3 \\ &\cdots\cdots\cdots\cdots \end{aligned} \qquad (2\text{-}7)$$

In general, we have

$$\bar{p}(n) = \bar{p}(0) * P^n \qquad \text{for the stationary chain } n = 0, 1, 2... \qquad (2\text{-}8)$$

Thus it is possible to find the probability that the system occupies each of its states after n moves, $\bar{p}(n)$, by postmultiplying the initial state probability vector $\bar{p}(0)$ by the n-th power of the transition matrix P.

2.1.2 Markov Decision Process

A Markov decision process is a stochastic sequential process. Consider a system that can be described by a discrete time Markov chain, where, furthermore, the decisions of each epoch and the returns are associated with each state we observe. Suppose a system whose state space has finitely many states. Let a state space S be a set of states labeled by the integers i=1, 2,...,N. That is, S = {1, 2,...,N}. For each $i \varepsilon S$, we have a set of K_i of finite actions (or alternatives) labeled by the integers k = 1, 2,..., K_i.

The policy space is denoted by the Cartesian product of each action set, that is $K = K_1 \times K_2 \times ... \times K_N$. Next, consider a sequential decision problem; that is, periodically observe one of the states at time t=0, 1, 2,..., and make a decision at each time.

When the system is in state $i \varepsilon S$ and we make an action $K \varepsilon K_i$, two things happen: (1) we obtain the return r_i^k and (2) the system transits to state j obeying the probability law $p_{ij}^k (j \varepsilon S)$ at the next time, given that system is in state i at that time and action k is made. Here we assume that the return r_i^k is bounded for all $i \varepsilon S$ and $k \varepsilon K_i$.

We also give an initial state distribution

$$\bar{p} = ({}_1p_o \, , {}_2p_o \, ,..., {}_Np_o) \qquad (2\text{-}9)$$

where

$$\sum_{i \varepsilon S} {}_ip_o = 1 \qquad {}_ip_o \geq 0 \qquad \text{for all } i \varepsilon S$$

The system is then a nonstationary Markov chain with returns. Our problem is to find strategies that maximize the total expected return over a finite-time or an infinite-time ($n \to \infty$) horizon, where a strategy is a sequence of decisions in each time and each state. Let F be a set of functions from the state space S to the policy space K. Since S and K are both finite sets, F is a finite set. Let f be a function in F, then a strategy U is defined by a sequence $\{f_n \, , \; n=1, 2,...\}$. Hence, we may write a strategy

$$U = \{f_1 \, , f_2 \, , \; ... \; , f_n \, , \; ...\} \qquad (2\text{-}10)$$

where f_n is the decision vector for each state at time n; that is, $f_n(i)$, the i-th element of f_n, is an action of state $i\varepsilon S$ at time n.

For any strategy U, we have a nonstationary Markov chain. Thus we write the n-step transition probability matrix as

$$P_n(U) = P(f_1)*P(f_2)*...*P(f_n) \quad \text{for } n = 1, 2,... \tag{2-11}$$

where $P(f_n)$ is the N x N transition matrix whose i-jth element is p_{ij}^k , $k=f_n(i)\varepsilon K_i$. For n=0, we define $P_o(U) = I$ (the N x N identity matrix). For any $f\varepsilon F$, we may write the N x 1 return vector r(f) whose i-th element is r_i^k , $k=f(i)\varepsilon K_i$. Under the notation defined above, let R be economic return, we have the N x 1 total expected return vector, ER, starting in each state $i\varepsilon S$:

$$ER(U) = \sum_{n=0} p_n\ (U) * \bar{r}\,(f_{n+1}) \tag{2-12}$$

Then, Markov decision process can be described as to choose an optimal strategy U*, which satisfy the vector inequality

$$ER(U^*) \geq ER(U) \tag{2-13}$$

There are three main algorithms to find an optimal strategy for a Markov decision process [25].

a. Howard's policy iteration algorithm;
b. Linear programming algorithm;
c. Dynamic programming algorithm.

For the models with a finite-time horizon, dynamic programming is very useful. Since one application of Markov decision processes is confined to finite-time horizon, we shall present a detailed discussion of the dynamic programming algorithm.

2.1.3 Dynamic Programming Algorithm

Using the same notation that we used in the preceding section, we first define a policy. A policy U is a sequence $(.....,f_n, \ ....,f_2, f_1)$ of members of F, where f_n is the decision for each state. That is, $f_n(i)$ is an action in state i measured n time backward from the end of the planning horizon. A policy U describes a backward sequence of actions in each state ending with f_1. The total expected return using n times of strategy U starting in each state $i\varepsilon S$ is

$$\overline{V}_n(U) = \bar{r}\,(f_n) + P(f_n)\,\bar{r}\,(f_{n-1}) + ... + P(f_n)P(f_{n-1}) ... P(f_2)\bar{r}\,(f_1) \tag{2-14}$$

for $n \geq 1$, where $\overline{V}_n(U)$ is the N x 1 column vector whose i-th element is the total expected return using n times of starting in state $i\varepsilon S$. From (2-14) we have the following recurrence relation:

$$\overline{V}_n(U) = \overline{r}(f_n) + P(f_n) * \overline{V}_{n-1}(U) \tag{2-15}$$

for $n \geq 1$, where $V_o(U) = 0$.

To find an optimal policy U*, we make use of dynamic programming, in particular, the principle of optimality. The principle of optimality states that an optimal policy has the property that despite the initial state and initial decisions, the remaining decisions must constitute an optimal policy for the state resulting from the first decision. Applying the principle of optimality, we have the following recurrence formula:

$$V_{n+1}(U^*)(i) = \underset{k \varepsilon K_i}{\text{Max}} \left[r_i^k + \sum_{j \varepsilon S} + p_{ij}^k * V_n(U^*)(j) \right] \tag{2-16}$$

for all $i \varepsilon S$ and for all $n \geq 0$, where

$$V_o(U^*)(i) = 0 \tag{2-17}$$

for all $i \varepsilon S$. Here $V_o(U^*)(i)$ is the ith element of $V_n(U^*)$. We can immediately obtain an optimal policy from (2-16) and (2-17).

2.2 Spatial Economic Model

During the past two decades, models of urban and regional evolution have been a topic of many studies in city planning. The main objective of these studies is to construct land use, development or spatial location models that describe or predict the geographical distribution of industry, commerce and residential population throughout an urban area. It is considered that if such models were successful, they could beneficially be used to predict future growth trends and determine, before the fact, the effect of various structural changes in the urban area. It is obvious that this ability would prove very useful to city and transportation planners, other government agencies, utilities and many commercial and service organizations.

Although urban and social systems have long been studied as having basic, nonlinear, dynamic properties in which the decisions of their human actors play an essential role, until recently, the conceptual and mathematical foundations for a substantive, scientific inquiry within that context have been lacking. The failure (or lack of sufficient success) of a number of urban systems projects during past decades have caused scientists to look for a new approach from conventional perception.

From the beginning of the 1980's, some new concepts have emerged from natural science related to the self-organization, or structural evolution, of complex systems. The new approach attempts to meet the nonlinear dynamic aspects of social systems. Having its roots in non-equilibrium analysis, the new approach mainly considers the evolution of a complex system as the result of interaction among the system components, and the evolution is not a deterministic process. For urban dynamics we can not build a clear, objective, quantified function. What we can do is perform an exploration of all possible futures, examining the stability and resilience of the various paths.

Based upon this philosophy, P.M. Allen et al. [5] developed the so-called spatial economic model. In the spatial economic model, a system is regarded as a group of subsystems. The difference between the system's goal and the state of the existing system, as well as the difference among the attributes of the subsystems, or in other words, the interaction among the subsystems, are the impetus of the evolution of the system. The evolution process of the system depends upon the attractivity of the subsystem to the system goal with some probability. The mathematical expressions of the spatial economic model are diversified for different situations. One of Allen's models is the following logistic equation:

$$\frac{dX_i^1(t)}{dt} = \partial * X_i^1(t) * \left[1 - \frac{X_i^1(t)}{\beta} \right] \tag{2-18}$$

where ∂, β are terms that depend upon the system being studied.

This is a potential starting point for future stochastic evolution studies. However, we shall go directly to the probabilistic formulation through Markov chains, thus by-passing Allen's dynamical equation formulation.

SECTION 3
PROBLEM FORMULATION

3.1 Introduction

Urban areas have a number of lifeline systems, some of which are categorized as follows:

Energy:	electricity, gas, liquid fuel
Water:	potable, flood, sewage
Transportation:	highway, railway, airport, harbor
Communication:	telephone and telegraph, radio, mail

Most lifelines consist of sources, major transmission lines, storage, and distribution or collection systems. Lifelines represent approximately 50% of the economic value vulnerable to an earthquake in an urban area. Past earthquake experience has demonstrated repeatedly that lifeline failure can produce severe consequences to the urban area. Examples of these consequences include:

a. Loss of service of the utility;
b. Direct financial loss;
c. Suspension of certain human activity, such as social activities, entertainment, commercial, etc.;
d. An inability to cope with secondary disaster such as fires, famines, and epidemics; and
e. Failure of a nature such that a lifeline itself becomes a hazard to life and property.

More specifically, essential lifeline interruptions can have immediate and serious effects upon a population, since:

a. Damaged transportation systems can impede evacuation or the arrival of disaster relief personnel and supplies;
b. Ruptured gas lines and severed electrical cables can be catalysts for fire;
c. Damaged water lines, storage tanks, and aqueducts can hamper fire fighting efforts and make potable water a rare commodity;
d. Ruptured sewer lines, municipal sewage tanks, and septic tanks can contaminate drinking water and render home toilets inoperative;
e. Downed telephone lines or damaged equipment can make it difficult for people in a stricken area to contact relatives and vice versa, or to immediately contact emergency relief agencies;
f. The interruption of gas and electrical service can make it difficult to heat or cool buildings, prepare food or boil water; and
g. All of the above can interrupt vital health services.

Past experience has shown that it can take weeks or even months to fully restore damaged lifeline services and years for the complete restoration of a destroyed source facility or distribution network. Damaged lifeline systems cannot satisfy all demands for the entire area before being completely restored. Additionally, the reconstruction resource is limited within the repair period. Therefore, the emergency management authority should assign different priorities of rescue operation for each subarea in order to minimize the total losses caused by malfunction of lifeline systems in whole urban areas (or, maximize the total return from the function of repaired lifeline system).

3.2 Problem Modeling

3.2.1 Basic Consideration

For post-earthquake reconstruction problems, we have the following consideration.

The reconstruction process of urban lifeline systems due to a major earthquake is a complex process, which involves both determinism and chance. The former is associated with available rescue resources, demand and supply for lifeline, and damage degree of system components. The latter includes secondary events, the interaction among the subsystems and other uncertainties. After a supposed catastrophic earthquake occurs, the lifeline systems may be severely destroyed and unable to function to capacity. The lifeline system cannot meet the requirements for demand from all subareas. When the emergency management authority develops mitigation and response plans for lifeline systems, the following basic facts should be taken into account.

a. An urban area consists of a number a subareas which are geographically formed with some specific characters, such as business, residential, industry, military and special districts (dam, nuclear plant, and so on). Thus, each subarea has a different importance order, economic and social, for the function of the whole urban area.

b. Because it is not possible to restore the damaged lifeline systems in all subareas simultaneously, the short supply of various lifelines to different subareas is inevitable. Furthermore, the returns from function of repaired lifeline systems in different subareas are quite different for the consideration of each subarea having different economic importance order.

c. The reconstruction resource varies during the entire restoration period since the available resource may be influenced by government aid and other factors.

d. The interaction among the subsystems may dramatically affect the restoration process in the entire area. For instance, the failure of a power system in subarea i may make it impossible to repair the water and transportation systems in subarea i as well as in the surrounding subareas.

Therefore, the decision-maker of reconstruction policy should answer the question: given limited rescue resources, including material and man-power, varying in each repair stage, how should they be assigned to different subsystems, considering the uncertainties involved in restoration process, in order to maximize the total return from functioning of a repaired lifeline system. This is a stochastic sequence decision problem. Markov decision process is a natural methodology to formulate and solve this kind of problem.

3.2.2 Capacity State of Subsystem

Let S(t) be the restoration process of a lifeline system indicating a level of state at time t after earthquake occurrence. Consider an urban system composed of N subsystems; we assume N_A subareas, and N_L lifelines. For simplicity of discussion, we set N_A x N_L = N subsystems. Thus, for example, for $N_A = 4$, $N_L = 2$, we shall consider a total of N = 8 subsystems. Then observe the capacity state ${}_nS(t)$ at time t of the nth subsystem. The capacity state ${}_nS(t)$ is assumed to take one of M different levels S_1, S_2,...,S_M dependent upon the degree of damage and the degree of restoration process, where S_i indicates the level of complete failure and S_M stands for the level of normal state, or full capacity. The intermediate states S_i , i = 2, 3, ..., M-1 indicate the level of damage, or capacity loss in the descending order.

Now imagine a time dependent variation of the restoration ${}_nS(t)$ shown in Figure 3-1. All subsystems start at level ${}_nS(0)$ at the instance of earthquake occurrence and are then restored to the normal state ${}_nS_M$ after some time. The total time required for the full restoration in given by T_M. Since the initial state at time t = 0 of ${}_oS(O)$ n = 1, 2,...,N is governed by chance and the restoration process involves many uncertainties, ${}_nS(t)$ are assumed to be random processes. Furthermore, since the present state ${}_nS(t)$ of the nth subsystem may depend upon the state at one step previous in time and is independent of any other previous times, we represent ${}_nS(t)$ as a discrete-state discrete-time Markov process (Markov chain).

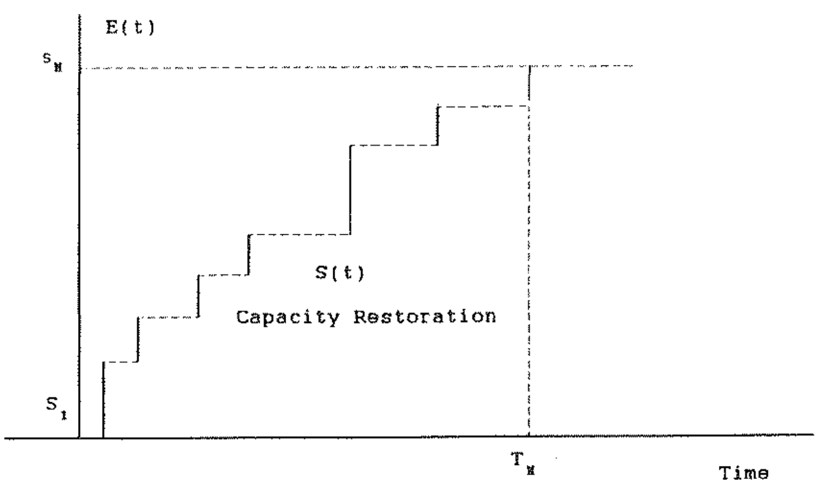

Figure 3-1 Restoration Curve of S(t)

The transition matrix is fundamental in the formulation of Markov chains. We assume the transition probabilities are functions of assigned rescue resource, geographical condition and structural character of the lifeline system. The transition probability may be written as

$$ {}_nP_{ij}\ (x_n, t+\Delta t) = \text{Prob}\ \{{}_nS(t+\Delta t) = j \mid {}_nS(t) = i \text{ and } x_n \text{ unit resources.}\} \quad (3\text{-}1)$$

The transition matrix whose components are ${}_np_{ij}(x_n,k\Delta t)$ is given as follows,

$$ {}_nP(x_n, k\Delta t) = \begin{vmatrix} {}_nP_{11}(x_n, k\Delta t)\ {}_nP_{12}(x_n, k\Delta t).....{}_nP_{1m}(x_n, k\Delta t) \\ {}_nP_{21}(x_n, k\Delta t)\ {}_nP_{22}(x_n, k\Delta t).....{}_nP_{2m}(x_n, k\Delta t) \\ \cdots\cdots\cdots \\ \cdots\cdots\cdots \\ {}_nP_{m1}(x_n, k\Delta t)\ {}_nP_{m2}(x_n, k\Delta t).....{}_nP_{mm}(x_n, k\Delta t) \end{vmatrix} \quad (3\text{-}2)$$

We assume the restoration process ${}_nS(k\Delta t)$ is a non-decreasing process either staying at the present state or shifting, by one step, to the next higher state during a time interval Δt. Thus, the probability transition matrix (3-2), assuming that state m is an absorbing state (no further increase possible), may be written as:

$$ {}_nP(x_n, k\Delta t) = \begin{vmatrix} 1-{}_np_{12}(x_n, k\ t)\ {}_np_{12}(x_n, k\Delta t) \\ 1-{}_np_{23}(x_n, k\Delta t)\ {}_np_{23}(x_n, k\Delta t) \\ \cdots\cdots\cdots \\ \cdots\cdots\cdots \\ 1-{}_np_{m-1,m-1}(x_n, k\Delta t)\ {}_np_{m-1,m}(x_n, k\Delta t) \\ 1 \end{vmatrix} \quad (3\text{-}3)$$

If the probability that ${}_nS\ (k\Delta t) = S_j$ is expressed by ${}_np_j(k\Delta t)$, then the probability state vector is given by

$$ {}_n\overline{S}\ (k\Delta t) = [{}_np_1(k\Delta t)\ ,\ {}_np_2(k\Delta t)\ ,\ ...{}_np_M(k\Delta t)] \quad (3\text{-}4)$$

where $\sum_{j=1}^{M} {}_np_j\ (k\Delta t) = 1.0$ for each k = 0, 1, 2,... .

The initial probability state vector, ${}_nS(0)$ must be evaluated from seismic risk analysis. If ${}_nS(0)$ is given, we can use equation (3-3) and (3-4) successively to determine

$$ {}_n\overline{S}\ (x_n, k\Delta t) = {}_n\overline{S}\ (0) * {}_nP(x_n, \Delta t) * {}_nP(x_n, 2\Delta t)...{}_nP(x_n, k\Delta t) \quad (3\text{-}5)$$

Equation (3-5) gives the probability law of the capacity restoration state of the nth subsystem at time t = k t in the post-earthquake recovery period.

3.2.3 Economic Return

Let ${}_n\overline{R}$ be the immediate economic return vector for subsystem N at capacity state i, i = 1, 2, 3,..., M,

$$ {}_n\overline{R} = [{}_n r(1) , {}_n r(2) ..., {}_n r(M)] \qquad (3\text{-}6)$$

We assume the immediate return is only a function of the system state and will take different values for distinct states. Because we cannot predict the exact state that the lifeline may be in after some time restoration period, we shall study the expected value of the economic return from functioning of lifeline systems.

$$ {}_n G (x_n) = {}_n\overline{R} * {}_n\overline{S} (x_n , k\ t)' \qquad (\text{"}'\text{" denotes transition}) \qquad (3\text{-}7)$$

The expected return ${}_nG(x_n)$ is a function of allocated resource and immediate return.

3.2.4 Optimal Allocation of Limited Resources

Dynamic programming is used to optimize the limited rescue resource distribution among various subsystems. In the following discussion, ${}_nG(x_n)$ is the only criterion for optimizing the rescue resource distribution during the post-earthquake restoration process. In order to use dynamic programming, we must make the following assumptions:

a. All rescue resources can be expressed in a common unit, such as monetary unit;
b. After a catastrophic earthquake, the available rescue resources are limited in each time period;
c. The return from each subsystem is independent of the resource allocation to the other subsystems;
d. The return functions are nondecreasing; and
e. The total return from all subsystems is equal to the sum of the individual returns.

With these assumptions, dynamic programming can be applied to the lifeline reconstruction process. In order to develop the dynamic programming functional equation for the resources allocation problem, we denote

$R(x_1, x_2, x_3,...,x_n)$ = total return from allocating x_n units of resource to the nth subsystem n = 1, 2,..., N.

${}_nG(x_n)$ = expected return from nth subsystem when x_n units of rescue resource are allocated to that subsystem.

x^* = maximum number of units of resource available to allocate to the whole system.

Then the problem we want to solve is

$$\text{Max } R(x_1, x_2, \ldots x_n) = \text{Max} \sum_{n=1}^{N} {}_n G(x_n) \tag{3-8}$$

subject to $\sum_{n=1}^{N} x_n = x*$; $x_n \geq 0$.

Equation (3-8) is solved by dynamic programming.

SECTION 4
SIMULATION

4.1 Simulation Flow Chart

The restoration of lifeline systems in the post-earthquake period is a complex, multidimensional process, involving many uncertainties. In addition, there are many factors that influence the restoration process of lifeline systems. Computer simulation is one approach to dealing with this kind of problem. By computer simulation, the combination of various scenario and reconstruction policies can be examined comprehensively. Then, optimal reconstruction policies under different situations can be inferred.

In our study, simulation has been divided into parts called "modules." A simplified block diagram showing the major modules is shown in Figure 4-1. Detailed discussions of simulation are in Section 5.

4.2 Numerical Examples

For simplicity, we set N = 8, M = 10 and the one step transition rate is assumed to be of the form

$$ {}_{n}p_{j}(x_{n}) = a_{n}*\{1-\exp(-b_{n}*x_{n}*(0.1*j)^{0.15})\} \tag{4-1}$$

The one step transition rate plays an important role in Markov chain method. Proper selection of the transition rate is the key point of successful application of Markov chain methodology. But the reconstruction process of damaged lifeline systems after catastrophic earthquakes is so complicated that it is impossible to find a suitable formula without integrated investigation of the reconstruction process. In this simulation, we chose formula (4-1) according to the following considerations:

a. The one step transition rate is the probability of a system changing from one state into another, so it must obey the probability law, i.e. $0 \leq p_j\,(x_n) < 1$.

b. The one step transition rate is a function of assigned resource. The more resource that is given to a system, the higher will be the transition rate for the system.

c. The one step transition rate will be affected by the geographical and structural conditions of the restored systems. In other words, the transition rate will be variable for distinct systems even with the same amount of resources.

d. The state of a damaged lifeline will have some influence on the transition rate of the system. The last term in formula (4-1) takes this factor into account.

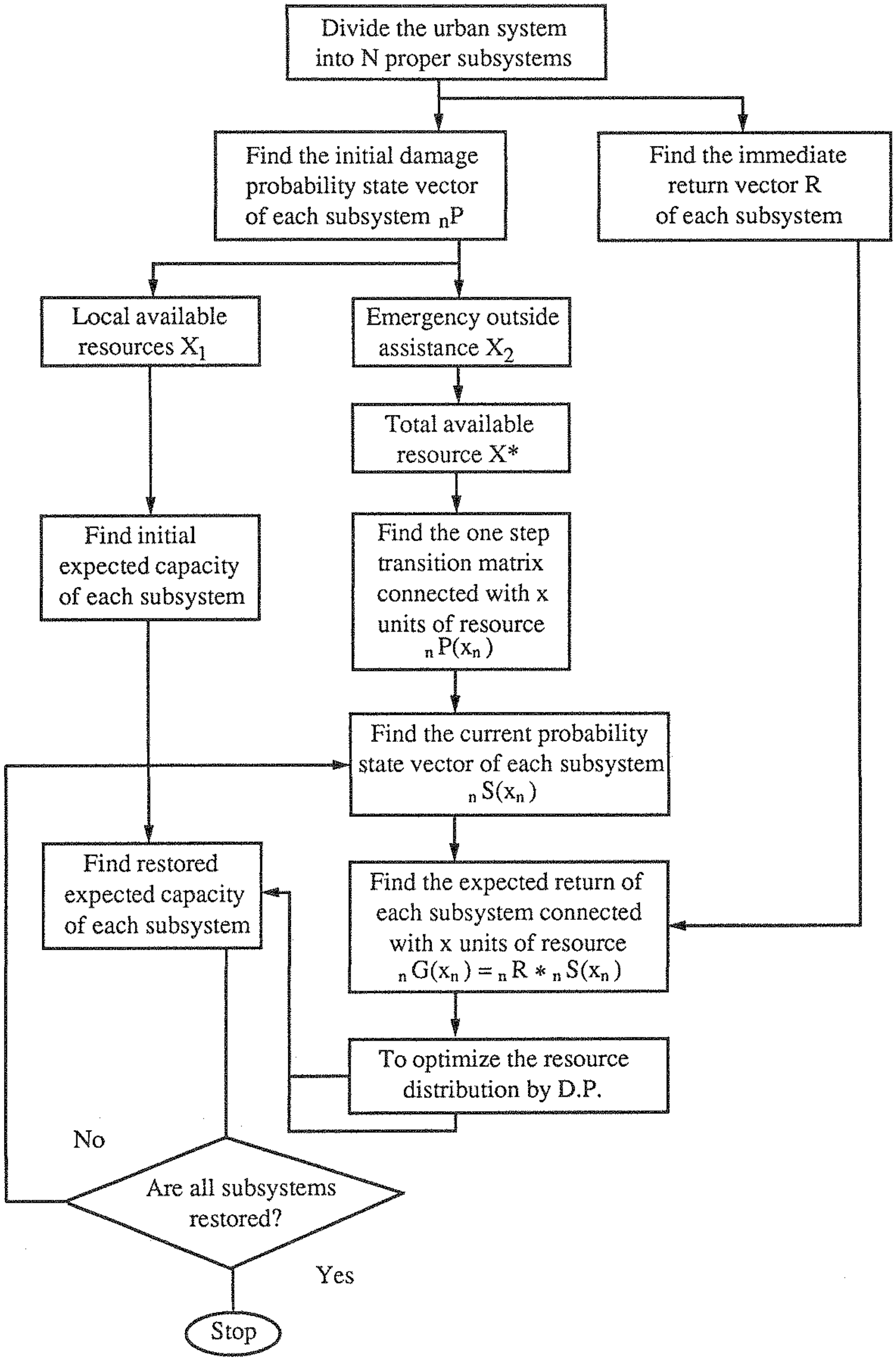

Figure 4-1 Simulation Diagram of Lifeline System Restoration Process

The total available resource in each restoration period is allowed to be variable and the restoration time T = 46 is assumed. Using the immediate return of subsystems in Table 4-I, different scenarios are designed to check the influence of various factors involved in the restoration process of lifelines in the post-earthquake period. The simulation was carried out with an IBM 4341 VM/CMS computer. The computer program is listed in the Appendix. The program consists of three main parts. Main routing manages the simulation environment, data input and result output. The second routing is to calculate the one step transition matrix, which is a function of available resource. The third routing is a typical dynamic programming subroutine which decides the optimal distribution of limited resource.

Table 4-I Immediate Return of Subsystem N at Different Capacity i

N\i	1	2	3	4	5	6	7	8	9	10
1	0	10	15	30	38	50	55	65	70	75
2	0	10	20	38	45	55	65	67	69	70
3	0	10	10	10	10	15	16	17	19	20
4	0	15	20	20	25	35	35	38	40	45
5	0	10	12	22	23	35	37	40	45	45
6	0	5	15	20	25	30	35	40	45	60
7	0	7	9	16	18	22	30	35	45	55
8	0	1	2	11	20	25	35	38	45	60

4.2.1 Case 1

This case uses the initial probability state vector in Table 4-II and transition parameters, including geographical and structural data in the Table 4-III. In this case, the rescue resource in each repair period varies, as given in Table 4-IV. Table 4-V is the optimal distribution of resource for each subsystem over whole reconstruction period. Fig. 4-2 shows the dynamic evolution of each subsystem.

Table 4-II Initial Probability State Vector of Case 1

N\i	1	2	3	4	5	6	7	8	9	10
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9
2	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0
3	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.2	0.5	0.3	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.3	0.2	0.5	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.6	0.3	0.1	0.0	0.0	0.0	0.0
8	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4-III Coefficients of Transition Rate Probabilities

$a_1 = .85$	$a_2 = .75$	$a_3 = .93$	$a_4 = .72$	$a_5 = .95$	$a_6 = .61$	$a_7 = .81$	$a_8 = .85$
$b_1 = .12$	$b_2 = .185$	$b_3 = .095$	$b_4 = .166$	$b_5 = .145$	$b_6 = .196$	$b_7 = .16$	$b_8 = .09$

Table 4-IV Available Resource in Each Repair Stage for Case 1

11	13	16	15	21	27	36	36	36	36	34	33	30	30	30	27	27	24	23	23	21	20	15
27	27	29	28	25	24	13	15	19	19	19	19	18	18	18	18	17	17	17	16	16	16	16

Table 4-V Optimal Distribution of Resource Among N Subsystem During Each Repair Period

T\N	1	2	3	4	5	6	7	8	OPT.RET at T-th peri.	TOT.RET.OF T peri
1	1	5	1	1	1	1	1	0	218.34	218.34
2	1	5	1	1	3	1	1	0	224.09	442.43
3	1	5	1	2	5	1	1	0	230.49	672.92
4	1	4	1	1	6	1	1	0	236.08	909.00
5	1	4	4	2	6	2	2	0	243.06	1152.07
6	1	4	4	3	7	4	4	0	251.02	1403.08
7	1	5	4	4	9	6	7	0	260.37	1663.46
8	1	4	3	4	8	6	10	0	269.37	1932.82
9	1	3	2	4	8	7	11	0	278.31	2211.13
10	1	3	1	4	7	8	12	0	287.26	2498.39
11	1	2	1	4	5	8	13	0	295.88	2794.27
12	1	1	1	4	4	9	13	0	304.17	3098.44
13	1	1	1	4	2	9	12	0	311.59	3410.03
14	1	1	1	4	2	9	11	1	318.38	3728.40
15	1	1	2	4	2	10	9	1	324.38	4052.78
16	1	1	1	4	2	10	7	1	329.38	4382.16
17	1	1	2	4	2	10	6	1	333.85	4716.01
18	1	1	2	4	1	10	4	1	337.54	5053.55
19	1	2	2	4	1	9	3	1	340.74	5394.28
20	1	1	3	4	2	9	2	1	343.58	5737.86
21	1	1	3	4	1	8	2	1	345.94	6083.80
22	1	1	3	3	2	7	2	1	347.95	6431.74
23	1	1	2	2	1	6	1	1	349.36	6781.10
24	1	3	6	4	3	6	3	1	351.48	7132.57
25	1	2	7	4	2	6	2	3	353.37	7485.94
26	1	2	7	3	2	5	1	8	355.28	7841.22
27	1	1	6	2	1	3	1	13	357.31	8198.53

Table 4-V Optimal Distribution of Resource Among N Subsystem During Each Repair Period (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET at T-th peri.	TOT.RET.OF T peri
28	1	1	3	1	1	1	1	16	359.63	8558.16
29	1	1	1	1	1	1	1	17	362.49	8920.65
30	1	1	1	1	1	1	1	6	364.21	9284.85
31	1	1	1	1	1	1	1	8	366.36	9651.21
32	1	1	1	1	1	1	1	12	369.28	10020.50
33	1	1	1	1	1	1	1	12	372.31	10392.81
34	1	1	1	1	1	1	1	12	375.41	10768.21
35	1	1	1	1	1	1	1	12	378.54	11146.75
36	1	1	1	1	1	1	1	11	381.52	11528.27
37	1	1	1	1	1	1	1	11	384.51	11912.78
38	1	1	1	1	1	1	1	11	387.49	12300.27
39	1	1	1	1	1	1	1	11	390.46	12690.73
40	1	1	1	1	1	1	1	10	393.20	13083.93
41	1	1	1	1	1	1	1	10	395.89	13479.82
42	1	1	1	1	1	1	1	10	398.49	13878.31
43	1	1	1	1	1	1	1	9	400.82	14279.13
44	1	1	1	1	1	1	1	9	403.05	14682.18
45	1	1	1	1	1	1	1	9	405.16	15087.34
46	1	1	1	1	1	1	1	9	407.13	15494.47

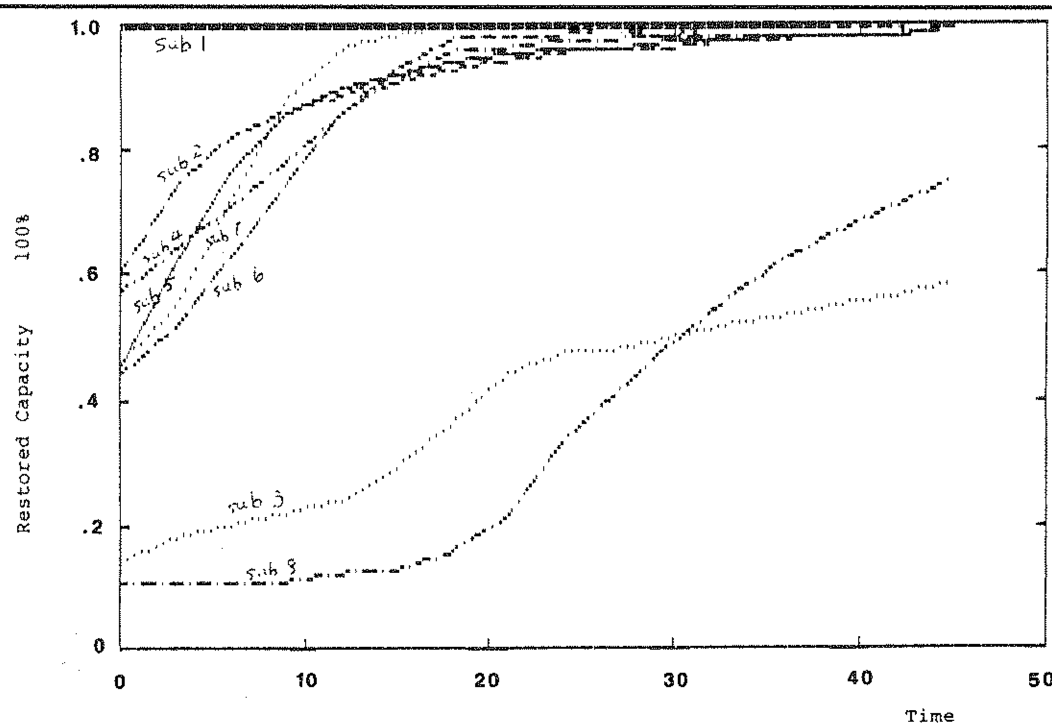

Figure 4-2 Restoration Curve of Lifelines in Case 1

4.2.2 Case 2

Case 2 uses the same data as in Case 1, except the initial probability state vector for some subsystems has been changed. Subsystem 1 changes from fully functional to totally destroyed and subsystem 8 from totally destroyed to a nearly functional state, so the influence of the initial damage state on the reconstruction policy can be seen. The supposed initial probability state vector for Case 2 is in Table 4-VI and Table 4-VII is the optimal distribution of rescue resource. Figure 4-3 shows the dynamic evolution of each subsystem.

Table 4-VI Initial Probability State of Case 2

N\i	1	2	3	4	5	6	7	8	9	10
1	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0
3	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.2	0.5	0.3	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.3	0.2	0.5	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.6	0.3	0.1	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	0.1	0.0

Table 4-VII Optimal Distribution of Resource Among the Subsystem N During Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	4	1	1	1	1	1	1	183.53	183.53
2	1	5	1	1	2	1	1	1	189.75	373.29
3	4	4	1	1	3	1	1	1	196.82	570.11
4	3	3	1	1	4	1	1	1	203.16	773.27
5	5	4	1	1	5	1	1	3	211.46	984.73
6	7	3	1	1	6	2	1	6	221.49	1206.22
7	9	3	2	2	6	3	3	8	234.06	1440.28
8	11	2	1	2	5	3	4	8	246.51	1686.79
9	12	2	2	1	5	3	5	6	258.86	1945.65
10	13	1	1	1	4	4	7	5	271.16	2216.80
11	13	1	1	1	3	4	8	3	282.98	2499.79
12	13	1	1	1	3	4	8	2	294.56	2794.34
13	12	1	1	1	2	4	8	1	305.28	3099.62
14	11	1	1	1	2	5	8	1	315.73	3415.35
15	11	1	1	1	2	5	8	1	325.77	3741.12
16	10	1	1	1	1	5	7	1	334.57	4075.69
17	9	1	1	1	1	6	7	1	342.79	4418.48

Table 4-VII Optimal Distribution of Resource Among the Subsystem N During Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
18	8	1	1	1	1	6	5	1	349.76	4768.23
19	7	1	1	1	1	6	5	1	356.03	5124.26
20	7	1	1	2	1	6	4	1	361.84	5486.10
21	6	1	1	2	1	6	3	1	366.85	5852.95
22	5	1	1	2	1	6	3	1	371.34	6224.29
23	4	1	1	1	1	5	1	1	374.64	6598.93
24	5	1	1	4	3	7	3	3	379.63	6978.55
25	5	1	1	4	3	7	3	3	384.18	7362.73
26	5	1	3	5	3	7	2	3	388.55	7751.29
27	5	2	3	5	2	6	2	3	392.40	8143.68
28	4	1	2	5	2	6	2	3	395.59	8539.27
29	4	1	3	5	2	5	2	2	398.39	8937.65
30	1	1	1	3	1	4	1	1	399.91	9337.56
31	2	1	1	4	1	4	1	1	401.53	9739.09
32	3	1	3	4	2	4	1	1	403.37	10142.43
33	3	1	3	4	1	3	2	2	405.06	10547.52
34	2	1	4	4	2	3	1	2	406.63	10954.14
35	2	2	5	3	1	3	1	2	408.08	11362.23
36	2	1	5	3	2	2	1	2	409.38	11771.61
37	2	1	6	3	1	2	2	1	410.61	12182.21
38	2	1	7	2	1	2	1	2	411.79	12594.00
39	2	1	8	2	1	2	1	1	412.94	13006.94
40	1	1	8	2	1	2	1	1	414.00	13420.94
41	1	1	9	1	1	2	1	1	415.05	13835.98
42	1	1	10	1	1	1	1	1	416.08	14252.06
43	1	1	9	1	1	1	1	1	417.04	14669.09
44	1	1	9	1	1	1	1	1	417.97	15087.06
45	1	1	9	1	1	1	1	1	418.86	15505.91
46	1	1	9	1	1	1	1	1	419.70	15925.62

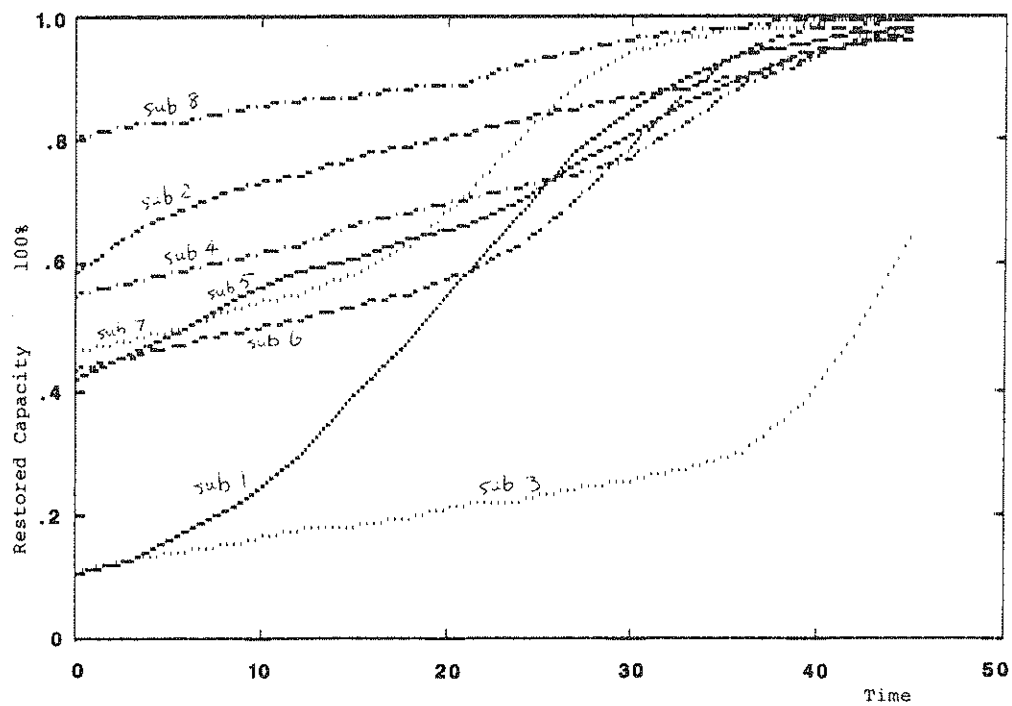

Figure 4-3 Restoration Curve of Lifeline for Case 2

4.2.3 Case 3

Parameters a_n and b_n in the transition rate formula (4-1) represent the geographical and structural characteristics of each subsystem, respectively. These parameters have tremendous influence on the restoration process of each subsystem, and then the optimal resource distribution. In order to check the influence of a_n and b_n, several scenarios were designed with changing values of a_n, and all other parameters fixed. Table 4-VIII shows the coefficients of transition rate probabilities for case 3. Table 4-IX is the optimal resource distribution in the new case. Figure 4-4 shows the dynamic evolution of each subsystem.

Table 4-VIII Coefficients of Transition Rate for Case 3

$a_1 = 0.1$	$a_2 = 0.2$	$a_3 = 0.3$	$a_4 = 0.4$	$a_5 = 0.5$	$a_6 = 0.6$	$a_7 = 0.7$	$a_8 = 0.8$

Table 4-IX Optimal Distribution of Resource Among the Subsystem N during Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	1	1	1	2	4	1	0	215.48	215.48
2	1	1	1	1	3	5	1	0	218.40	433.88
3	1	1	1	2	4	5	2	0	221.95	655.84

Table 4-IX Optimal Distribution of Resource Among the Subsystem N during Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
4	1	1	1	1	3	5	3	0	225.37	881.22
5	1	2	1	1	5	6	5	0	230.04	1111.26
6	1	3	1	2	6	7	7	0	235.95	1347.21
7	1	4	1	4	8	8	10	0	243.47	1590.67
8	1	4	1	3	7	9	11	0	251.29	1841.96
9	1	4	1	2	7	9	12	0	259.40	2101.36
10	1	3	1	2	6	10	12	1	267.66	2369.02
11	1	3	1	1	6	9	12	1	275.52	2644.54
12	1	3	1	1	5	9	12	1	282.98	2927.52
13	1	2	1	1	4	9	11	1	289.56	3217.08
14	1	3	1	1	5	8	10	1	295.57	3512.65
15	1	3	1	2	5	8	9	1	300.98	3813.64
16	1	3	1	2	4	8	7	1	305.46	4119.09
17	1	3	1	2	5	7	7	1	309.47	4428.55
18	1	3	1	2	5	6	5	1	312.74	4741.30
19	1	3	1	3	4	6	4	1	315.63	5056.93
20	1	4	1	3	5	5	3	1	318.29	5375.21
21	1	4	1	3	4	4	3	1	320.57	5695.78
22	1	4	1	3	4	4	2	1	322.63	6018.40
23	1	3	1	2	3	3	1	1	324.12	6342.52
24	1	5	4	5	5	4	2	1	326.54	6669.06
25	1	5	4	5	5	3	2	2	328.83	6997.89
26	1	5	4	5	4	3	2	5	331.16	7329.05
27	1	4	3	5	4	2	1	8	333.44	7662.48
28	1	3	1	4	2	1	1	12	335.67	7998.15
29	1	2	1	3	1	1	1	14	338.18	8336.33
30	1	1	1	1	1	1	1	6	339.77	8676.10
31	1	1	1	1	1	1	1	8	341.76	9017.86
32	1	1	1	1	1	1	1	12	344.44	9362.29
33	1	1	1	1	1	1	1	12	347.28	9709.57
34	1	1	1	1	1	1	1	12	350.23	10059.80
35	1	1	1	1	1	1	1	12	353.25	10413.05
36	1	1	1	1	1	1	1	11	356.16	10769.21
37	1	1	1	1	1	1	1	11	359.10	11128.31
38	1	1	1	1	1	1	1	11	362.04	11490.35
39	1	1	1	1	1	1	1	11	364.99	11855.34
40	1	1	1	1	1	1	1	10	367.75	12223.08
41	1	1	1	1	1	1	1	10	370.49	12593.57

Table 4-IX Optimal Distribution of Resource Among the Subsystem N during Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
42	1	1	1	1	1	1	1	10	373.18	12966.75
43	1	1	1	1	1	1	1	9	375.65	13342.39
44	1	1	1	1	1	1	1	9	378.05	13720.44
45	1	1	1	1	1	1	1	9	380.38	14100.81
46	1	1	1	1	1	1	1	9	382.61	14483.42

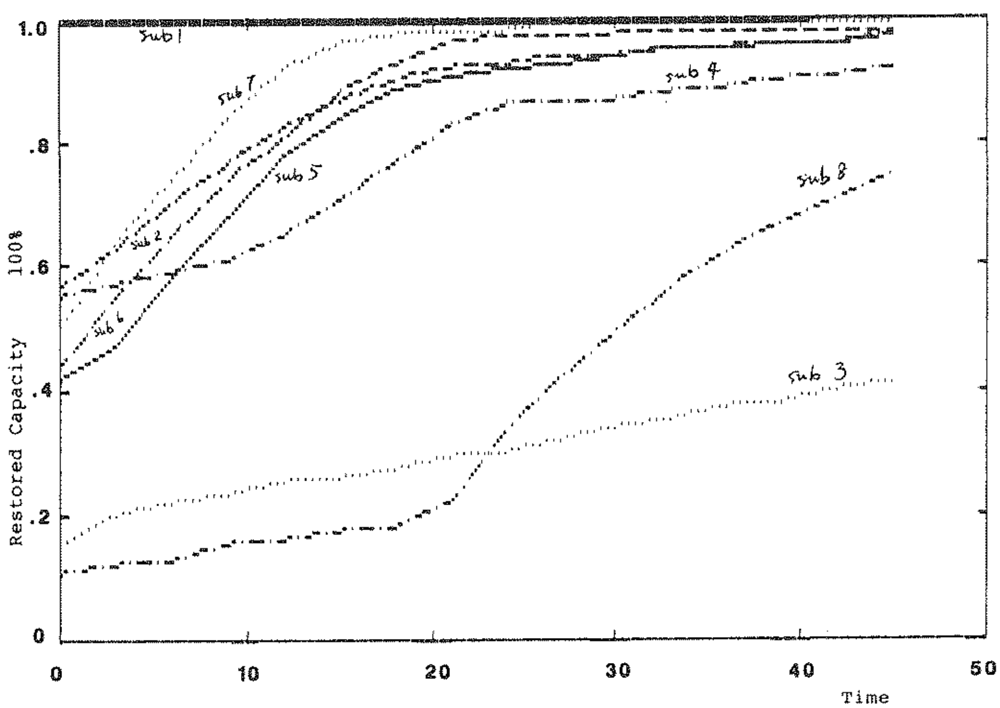

Figure 4-4 Restoration Curve of Lifeline in Case 3

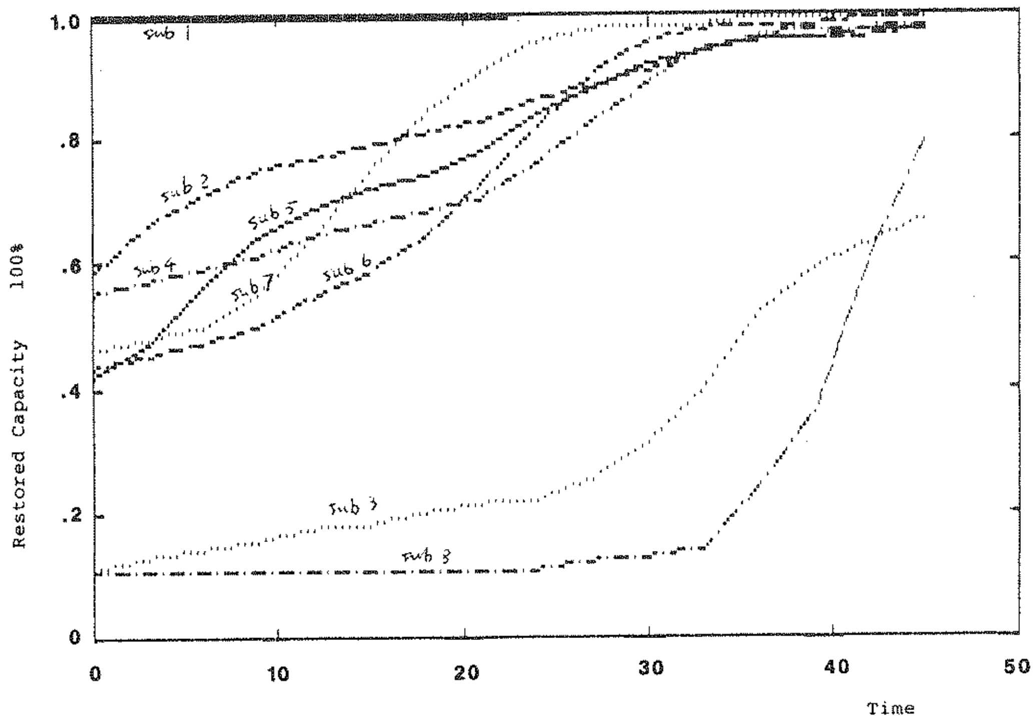

Figure 4-5 Restoration Curve of Lifeline in Case 4

4.2.4 Case 4

If the total available resources are fixed for the entire reconstruction period, the management authority should decide how to use the limited resource over the whole planning horizon. Generally speaking, there are three choices:

a. Distribute the resource evenly during the whole reconstruction period;
b. Allocate as many resources as possible to the damaged system during the earlier repair stage;
c. Increase resource supply after some time period.

At first glance, choice b seems most reasonable. But in reality, the management authority may choose alternative c. They will slow down the restoration process and wait for more outside aid [23]. Furthermore, the efficiency of resources employed during earlier repair periods may be less than that of later periods, due to insufficient information, poor planning and possible second events during earlier restoration periods.

Table 4-X is supposed resource supply planning for the entire repair period. In this case, the resource supply planning adopts choice c, and the resource supply will be increased gradually. Table 4-XI is the optimal resource distribution and total economic return for this case with the same parameters as case 1. Fig. 4-5 shows the influence of resource supply planning on the total optimal return.

Table 4-X Available Resource Supply for Each Repair Stage

11	11	11	11	11	11	11	11	12	12	12	12	13	13	13	13	14	14	15	15	15	21	21
23	24	25	26	27	28	30	30	30	30	30	33	36	36	36	36	36	36	36	36	36	36	36

Table 4-XI Optimal Distribution of Resource Among Subsystem N During Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	5	1	1	1	1	1	0	218.34	218.34
2	1	4	1	1	2	1	1	0	223.22	441.56
3	1	4	1	1	2	1	1	0	227.76	669.32
4	1	3	1	1	3	1	1	0	232.03	901.34
5	1	2	1	1	4	1	1	0	236.10	1137.44
6	1	2	1	1	4	1	1	0	240.03	1377.47
7	1	2	1	1	4	1	1	0	243.80	1621.27
8	1	2	1	1	4	1	1	0	247.40	1868.67
9	1	1	1	1	4	2	2	0	251.18	2119.85
10	1	1	1	1	3	2	3	0	254.90	2374.75
11	1	1	1	1	3	2	3	0	258.61	2633.36
12	1	1	1	1	2	2	4	0	262.35	2895.71
13	1	1	1	1	2	2	5	0	266.47	3162.17
14	1	1	1	1	1	2	6	0	270.67	3432.84
15	1	1	1	1	1	2	6	0	274.97	3707.82
16	1	1	1	1	1	2	6	0	279.31	3987.13
17	1	1	1	1	1	3	6	0	283.92	4271.04
18	1	1	1	1	1	3	6	0	288.44	4559.48
19	1	1	1	1	1	4	6	0	293.10	4852.58
20	1	1	1	1	1	4	6	0	297.57	5150.14
21	1	1	1	1	1	5	5	0	301.82	5451.96
22	1	1	1	1	4	6	7	0	307.17	5759.13
23	1	1	1	2	3	7	6	0	312.17	6071.30
24	1	1	1	3	4	8	5	0	317.19	6388.48
25	1	2	1	4	3	8	5	0	322.02	6710.50
26	1	2	1	4	3	9	4	1	326.65	7037.15
27	1	1	2	5	3	9	4	1	330.95	7368.10
28	1	2	3	5	3	9	3	1	335.01	7703.11
29	1	2	4	5	3	9	3	1	338.79	8041.89
30	1	2	5	6	3	9	3	1	342.34	8384.23
31	1	3	4	6	3	9	3	1	345.48	8729.71
32	1	2	6	6	3	8	3	1	348.24	9077.96

Table 4-XI Optimal Distribution of Resource Among Subsystem N During Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
33	1	2	7	6	3	8	2	1	350.67	9428.62
34	1	2	8	6	3	7	2	1	352.82	9781.45
35	1	2	9	5	3	6	2	5	354.92	10136.36
36	1	2	10	4	1	5	2	11	357.12	10493.48
37	1	1	9	2	1	4	1	17	359.64	10853.12
38	1	1	7	1	1	2	1	22	362.91	11216.03
39	1	1	5	1	1	1	1	25	367.05	11583.08
40	1	1	3	1	1	1	1	27	371.81	11954.89
41	1	1	3	1	1	1	1	27	376.85	12331.73
42	1	1	3	1	1	1	1	27	381.96	12713.69
43	1	1	3	1	1	1	1	27	387.04	13100.73
44	1	1	3	1	1	1	1	27	392.12	13492.85
45	1	1	3	1	1	1	1	27	397.21	13890.06
46	1	1	3	1	1	1	1	27	402.23	14292.29

4.2.5 Case 5

As we mentioned above, the one step transition rate formula plays an important role in this simulation. The proper choice of a transition rate formula will make the simulation more indicative of the real restoration process. A poorly chosen formula will lead to failure of this methodology. In the above simulation examples, an exponential formula was employed. In the present simulation case, the following transition rate formula is used.

$$ {}_n p_j(x) = \frac{a_n * X * (0.1*j)^{0.15}}{d + b_n * X} \qquad (4\text{-}2) $$

In formula (4-2), a_n and b_n have the same definition as in (4-1), and parameter d is a special term which makes the formula meet the requirement of a probability law.

Figure 4-6 shows the relation between transition rates and available resource for the exponential formula (4-1) and Figure 4-7 is for equation (4-2).

Table 4-XII is the simulation result for this case with same parameters as case 1.

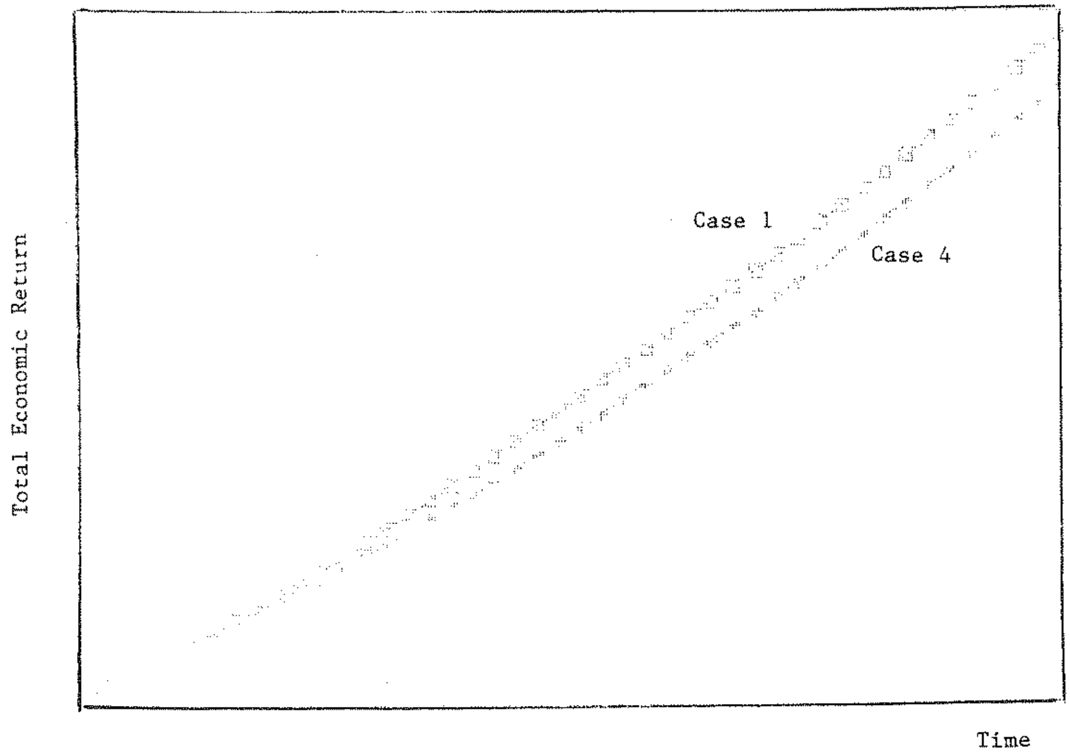

Figure 4-6 Comparison of Total Optimal Economic Return Between Case 1 and Case 4

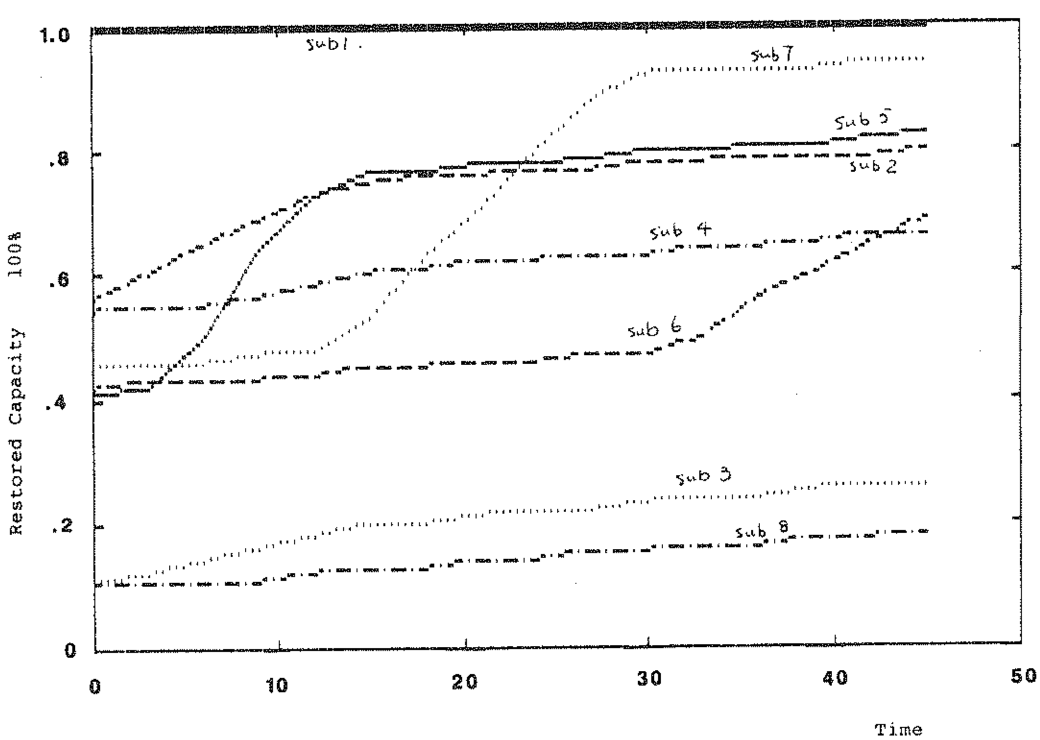

Figure 4-7 Restoration Curve of Lifeline in Case 5

Table 4-XII Optimal Distribution of Resource Among Subsystem N for Each Repair Stage

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
1	1	5	1	1	1	1	1	0	214.53	214.53
2	1	7	1	1	1	1	1	0	216.38	430.91
3	1	10	1	1	1	1	1	0	218.64	649.55
4	1	6	4	1	1	1	1	0	220.63	870.17
5	1	9	4	1	4	1	1	0	223.38	1093.55
6	1	8	3	1	12	1	1	0	226.82	1320.38
7	1	7	5	1	20	1	1	0	231.34	1551.71
8	1	7	1	1	23	1	1	1	235.67	1787.39
9	1	6	5	1	20	1	1	1	239.62	2027.01
10	1	8	4	1	19	1	1	1	243.27	2270.28
11	1	7	3	3	17	1	1	1	246.44	2516.72
12	1	7	4	5	13	1	1	1	249.30	2766.02
13	1	6	3	6	11	1	1	1	251.72	3017.75
14	1	7	5	5	9	1	1	1	253.99	3271.74
15	1	5	1	5	6	3	8	1	256.15	3527.89
16	1	1	1	1	1	4	17	1	258.14	3786.03
17	1	1	1	1	1	1	20	1	260.37	4046.39
18	1	1	1	1	1	1	17	1	262.57	4308.96
19	1	1	1	1	1	1	16	1	264.83	4573.79
20	1	1	1	1	1	1	16	1	267.22	4841.01
21	1	1	1	1	1	1	14	1	269.45	5110.46
22	1	1	1	1	1	1	13	1	271.60	5382.06
23	1	1	1	1	1	1	8	1	273.11	5655.16
24	1	1	1	1	1	1	20	1	276.14	5931.30
25	1	1	1	1	1	1	20	1	279.13	6210.44
26	1	1	1	1	1	1	22	1	282.24	6492.68
27	1	1	1	1	1	1	21	1	285.03	6777.71
28	1	1	1	1	1	1	18	1	287.30	7065.01
29	1	1	1	1	1	1	17	1	289.28	7354.29
30	1	1	1	1	1	1	6	1	290.18	7644.47
31	1	1	1	1	1	1	8	1	291.21	7935.68
32	1	1	1	1	1	4	9	1	292.50	8228.18
33	1	1	1	1	1	8	5	1	293.75	8521.93
34	1	1	1	1	1	11	2	1	294.99	8816.92
35	1	1	1	1	1	12	1	1	296.23	9113.15
36	1	1	1	1	1	11	1	1	297.42	9410.57
37	1	1	1	1	1	11	1	1	298.61	9709.18
38	1	1	1	1	1	11	1	1	299.81	10008.99

Table 4-XII Optimal Distribution of Resource Among Subsystem N for Each Repair Stage (Continued)

T\N	1	2	3	4	5	6	7	8	OPT.RET. at T-th peri.	TOT.RET.OF T peri.
39	1	1	1	1	1	11	1	1	301.03	10310.02
40	1	1	1	1	1	10	1	1	302.18	10612.20
41	1	1	1	1	1	10	1	1	303.35	10915.54
42	1	1	1	1	1	10	1	1	304.52	11220.06
43	1	1	1	1	1	9	1	1	305.63	11525.69
44	1	1	1	1	1	9	1	1	306.74	11832.43
45	1	1	1	1	1	9	1	1	307.86	12140.28
46	1	1	1	1	1	9	1	1	308.98	12449.27

SECTION 5
DISCUSSION AND POLICIES SELECTION

5.1 Simulation Analysis

In this simulation, five scenarios were examined, each with several cases. Comparing the simulation results, it can be seen how different factors affect the reconstruction process and the kinds of policies that should be adopted under the different situations.

The curve of evolution of subsystem 1 in case 1 experiences little change over time, because the initial probability state of subsystem 1 is nearly in the normal state. The subsystem 8 in the same case does not receive any resource at the beginning of the reconstruction process. At first glance, it appears unreasonable because the initial probability state vector is in a completely destroyed state. The emergency management authority would be expected to assign some rescue resource to the subsystem. But by carefully examining the economic return table, it can be seen that the economic return from functioning of subsystem 8 is very small. Since the criterion of optimizing the resource distribution is to maximize the total economic return from functioning of the entire lifeline system, subsystem 8 does not receive any rescue resource until other subsystems are nearly restored. Keep in mind that the subsystems are independent in this simulation. Dependence would introduce other considerations.

In case 2, the influence of initial damage probability on the reconstruction policy is checked. Compared with case 1, subsystem 8 receives some resources at the beginning of the restoration process. Although subsystem 1 is a completely destroyed state, it does receive rescue resources at the beginning of the restoration process. The result is different from subsystem 8 in case 1, where subsystem 8 does not receive any resource when it is in the totally destroyed state. From the return table, we see that subsystem 1 has a very high return even at lower states of capacity. This is why subsystem 1 receives rescue resource at lower capacity states.

In the transition rate formula, a_n and b_n are defined as geographical and structural characteristic parameters of the n-th subsystem, respectively. These two parameters will influence the transition rate dramatically. Comparing case 1 and 3, all final capacities in case 3 are reduced tremendously, because all a_n in case 3 are less than the corresponding values in case 1. The smaller the value a_n, the lower the final restored capacity. Consequently, the total expected return in case 3 is less than that of case 1, though the same amounts of resources were applied. Larger values of a_n, which may represent better geographical environments after the earthquake, may lead to higher restoration rates with fixed resources.

Case 1 and case 4 are compared to determine the influence of the resource supply policy on the restoration process. In both cases, the total available resources are the same for the entire planning horizon, but with different resource supply policies. In case 4, less resources were supplied to the earlier reconstruction process and more resources became available as the repair process evolved. Comparing the restoration processes of the two cases, the lifelines in case 1 were restored at a faster rate at earlier repair stages, though the final restored capacity is nearly the same for both cases. The total expected return in case 1 is a little higher than that in case 4. The lifelines in case 1 were restored to higher capacity in the earlier stage, and greater economic return was obtained. Therefore, it seems reasonable to supply as many resources as possible to the restoration process in the entire reconstruction period, assuming other considerations, such as waiting for outside aid, are neglected.

In case 5, a linear transition rate formula is used to replace the exponential formula. Both formulas have reasonable characteristics. In the linear formula, more resources are allocated to a damaged lifeline, so the restoration rate of the system is higher. But considering the restraint of "space," the restoration rate cannot be expected to increase without limitation. With the exponential formula, the restoration speed will grow at a lower increase rate when the resources increase. After the supplied resource grows beyond some level, saturation occurs and the restoration rate stays constant. Comparing Fig. 5-1 and Fig. 5-2 shows that the choice of the transition rate formula is so important that the formula will decide whether or not the simulation is applicable.

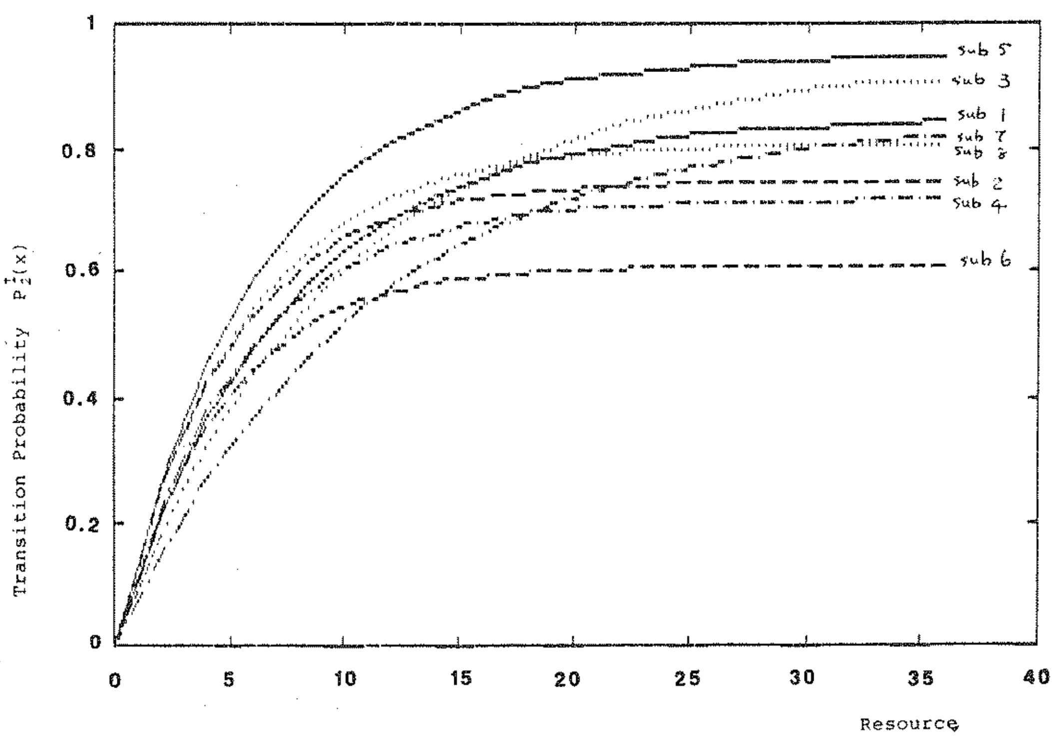

Figure 5-1 Exponential Transition Rate Curve

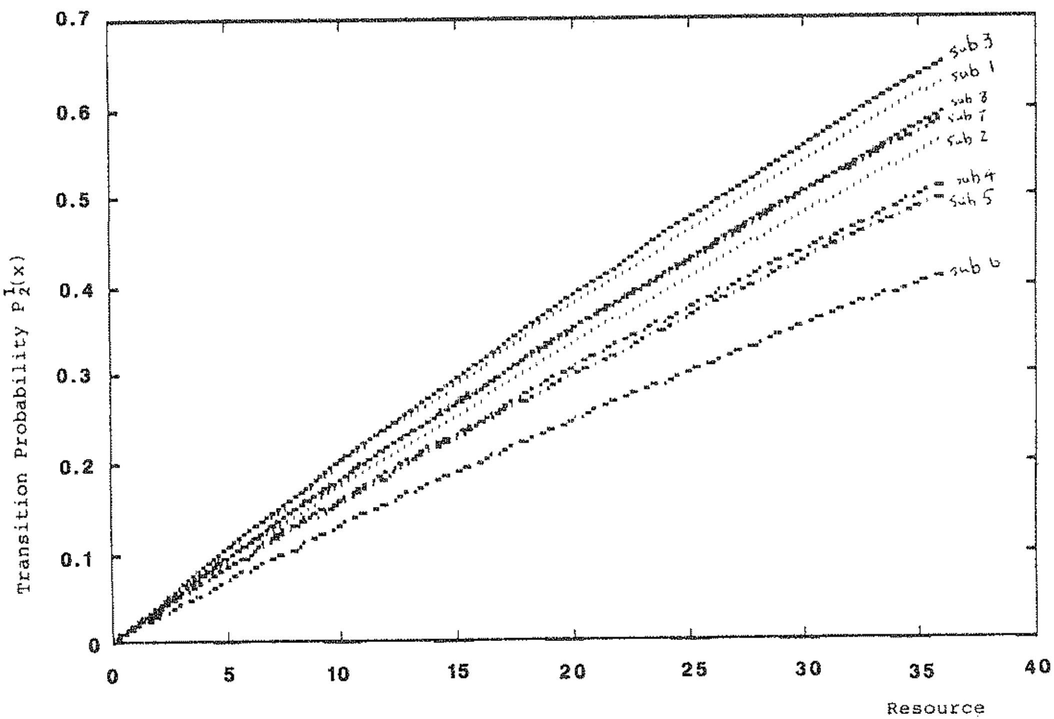

Figure 5-2 Linear Transition Rate Curve

5.2 Policy Recommendations

According to the simulation results, based on independent subsystems, the emergency management authority should assume the following descending priority for reconstruction policy. This assumes that the initial damage probability state and immediate economic return are the only two prevailing factors to influence the restoration processes.

a. Subsystems with higher economic return and lower damage probability state;
b. Subsystems with higher economic return and higher damage probability state;
c. Subsystems with lower economic return and lower damage probability state;
d. Subsystems with lower economic return and higher damage probability state.

The coefficient of a_n and b_n in the formula of transition rate represent the geographical and structural characteristics of a restored lifeline system, respectively. These two parameters influence the transition rate dramatically. Generally speaking, higher a_n and b_n leader to higher restoration rates. Therefore, the emergency management authority should assign higher priority to the subsystems with higher a_n and b_n.

SECTION 6
CONCLUSIONS

6.1 Summary

The objective of this research is twofold. First, is to extend the current state of knowledge in understanding the dynamic response of lifeline systems due to a catastrophic earthquake. Second, to recommend an optimal reconstruction strategy to the emergency management authority when mitigation and preparedness plans are developed. For the past twenty years, researchers have devised a number of methodologies to study the behavior of lifeline systems subject to earthquakes, statically or dynamically. Most, if not all, of these procedures do not study the problem of lifeline system response as a complete urban system. It is felt that the problem cannot be thoroughly understood without integrating the many disciplinary studies concerning earthquakes into a comprehensive view of the urban system.

The current investigation considers the lifeline system as a complex, multidimensional, stochastic and dynamic system during the period following the earthquake. Markov decision process is employed in this formulation.

6.2 Conclusions

The major results of this study are:

a. A theoretical formulation of seismic damage restoration processes for general independent lifeline systems is developed in terms of Markov chains. The optimal reconstruction policy is obtained according to the criterion of maximizing the expected economic return from the functioning of the lifeline system.

b. The methodology developed here can apply to general lifeline systems to estimate the time required for various capacity restorations. For example, in case 1, it is estimated that about 16 time periods are required for the 95% capacity restoration of subsystem 7.

c. By simulation, various scenarios are examined to determine the influence of different factors in the restoration process of lifeline systems. Initial damage probability states and immediate economic returns of lifeline systems are the two main factors in deciding reconstruction policy for an assumed probabilistic transition matrix.

6.3 Recommendations for Future Research

Future research directions are suggested below:

a. Accurate formulation of transition rate is critical for the validation of this model. Various possible functional forms should be investigated in order to choose the most suitable function to represent the realistic situation.

b. Interactions among subsystems are important factors which influence the restoration process of lifelines. Malfunction of subsystem i may delay the restoration process of subsystem j, or even make the restoration process of subsystem k impossible. In future studies, interactions among subsystems will be taken into account.

c. The determination of immediate economic return is so important that this model will fail without appropriate return data for each subsystem. Therefore, careful definition and collection of economic return data for each subsystem is a prerequisite to the application of this approach.

SECTION 7
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Appendix

Computer Program for Simulation

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C*********************************************************************
C*   THIS PROGRAM IS DESIGNED TO SIMULATE THE RECONSTRUCTION PROCESS *
C* OF A DAMAGED URBAN LIFELINE SYSTEM BY MEANS OF MARKOV MODEL. THE  *
C* OBJECTIVE OF THE SIMULATION IS TO FIND AN OPTIMAL ALLOCATION OF   *
C* LIMITED RECONSTRUCTION RESOURCES IN ORDER TO MAXIMIZE THE TOTAL   *
C* ECONOMIC RETURN FROM THE FUNCTIONING OF THE DAMAGED LIFELINE      *
C* SYSTEM.                                                           *
C*   TO RUN THIS PROGRAM, THE FOLLOWING DATA ARE NEEDED TO READ      *
C*    T--------THE TIME PERIOD OF SIMULATION;                        *
C*    SOU(I)---THE TOTAL AVAILABLE RESOURCE IN PERIOD I;             *
C*    N--------NUMBER OF LIFELINE SYSTEMS;                           *
C*    S--------NUMBER OF SUBAREAS IN THE STUDY REGION;               *
C*    R(I,J)---IMMEDIATE ECONOMIC RETURN OF I-TH LIFELINE AT J-TH    *
C*             CAPACITY(STATE);                                      *
C*    P(I,J)---INITIAL DAMAGE PROBABILITY OF I-TH LIFELINE AT J-TH   *
C*             STATE;                                                *
C*    A(I)-----GEOGRAPHICAL PARAMETER OF I-TH LIFELINE;              *
C*    B(I)-----STRUCTURAL PARAMETER OF I-TH LIFELINE.                *
C*                                                                   *
C*   TO CALCULATE                                                    *
C*    PROB(J,I,X)---PROBABILITY OF I-TH LIFELINE AT J-TH STATE WHEN  *
C*                  X UNITS OF RESOURCE WAS ALLOCATED;               *
```

```
C*    D(I,X)--------THE OPTIMAL UNIT OF RESOURCE TO ALLOCATE TO I-TH *
C*                  LIFELINE WHEN ONLY LIFELINE I, I+1,..., N ARE   *
C*                  BEING CONSIDERED AND X-1 UNITS RESOURCE ARE     *
C*                  AVAILABLE;                                      *
C*    G(I,X)--------EXPECTED ECONOMIC RETURN OF I-TH LIFELINE WHEN  *
C*                  X UNITS OF RESOURCE ARE ALLOCATED;              *
C*    F(I,X)--------THE OPTIMAL RETURN FROM ALLOCATING (X-1) UNITS  *
C*                  OF RESOURCE IN LIFELINE I,I+1,...,N(I=1,2,..,N) *
C*                                                                  *
C*******************************************************************
C     MAIN PROGRAM
      DIMENSION F(8,101),R(8,10),A(8),P(8,10),Q(10,10),G(8,101),U(10,8,
     1101),B(8),EX(8,48),EIP(8),CAP(50,8),RET(50),TRET(50)
      INTEGER X,Z,SUM,XSTAR(8),Q,QP,D(8,101),Y,V,W,T,S,TM,SOU(46),TAR(8)
     2,DIST(50,8),TSOU,KK
      COMMON A,P,T,B,TM,V
      REAL CO,TRT
      READ(5,54) (SOU(I),I=1,46)
54    FORMAT(2(23I3/))
      READ(5,55)N,T,S,KK
55    FORMAT(4I6)
      READ(5,56) (A(I),I=1,8)
56    FORMAT(8F7.3)
      READ(5,58) (B(I),I=1,8)
58    FORMAT(8F7.3)
```

```
      READ(5,*) ((R(I,J),J=1,10),I=1,8)
      READ(5,*) ((P(I,J),J=1,10),I=1,8)
      TSOU=0
      DO 59 I=1,46
      TSOU=TSOU+SOU(I)
59    CONTINUE
      WRITE(6,53) KK
53    FORMAT(9X,'SIMULATION OF CASE',I4/)
      WRITE(6,60) N,S,TSOU
60    FORMAT(3X,'THE NO.OF SUBAREA IS',I2,', THE NO.OF SYS.IS,',I2,' THE
     2 TOTAL AVAI.RESOU.DUR.RECON.PERIOD IS',I5/)
      WRITE(6,61) T
61    FORMAT(' SUPPOSING',I3,' TIME OF PERIODS RECONSTRUCTION'/)
      WRITE(6,63) (A(I),I=1,8)
63    FORMAT(' THE COE. OF A(I) IS  ',8F7.3)
      WRITE(6,69) (B(I),I=1,8)
69    FORMAT(' THE COF. OF B(I) IS  ',8F7.3/)
      WRITE(6,66)
66    FORMAT(5X,'  THE AVAILABLE RESOURCE AT EACH RECOVERY PERIOD'/)
      WRITE(6,71) (SOU(I),I=1,46)
71    FORMAT(23I3)
      WRITE(6,16)
16    FORMAT(/5X,' IMMEDIATE ECONOMIC RETURN TABLE'/)
      WRITE(6,68) ((R(I,J),J=1,10),I=1,8)
```

```
68    FORMAT(8(10F6.0/))
      DO 41 I=1,8
      EIP(I)=0.0
      DO 42 M=1,10
42    EIP(I)=EIP(I)+M*P(I,M)
41    CONTINUE
      WRITE(6,27) KK
27    FORMAT(10X,'SIMULATION RESULT OF CASE',I3/)
      WRITE(6,73)
73    FORMAT(5X,' PROB.OF.INI.STA.IN SUBAREA',24X,'EXP.CAPA.')
      WRITE(6,72)  ((P(I,J),J=1,10),EIP(I),I=1,8)
72    FORMAT(8(10F6.1,F8.2/))
      TRT=0.0
      DO 1000 TM=1,T
      K=SOU(TM)+1
      DO 201 N=1,8
      DO 202 X=1,K
      EX(N,X)=0.0
      DO 203 M=1,10
      U(M,N,X)=PROB(M,N,X)
      EX(N,X)=EX(N,X)+M*U(M,N,X)
203   CONTINUE
      WRITE(6,25) N,X,TM
25    FORMAT(' SYS.PROB.OF',I2,'TH SUBSYS.WITH',I3,' UNIT RESO. AFTER
```

```
    2PERIOD',I2/)
      WRITE(6,75) (U(M,N,X),M=1,10),EX(N,X)
75    FORMAT(11F7.4/)
202   CONTINUE
201   CONTINUE
      DO 110 N=1,8
      G(N,1)=0
110   CONTINUE
      DO 120 N=1,8
      DO 130 X=2,K
      G(N,X)=0
      DO 140 M=1,10
      G(N,X)=G(N,X)+U(M,N,X)*R(N,M)
140   CONTINUE
130   CONTINUE
120   CONTINUE
      DO 129 N=1,8
      DO 129 X=2,K
      IF ((EX(N,X)-10.0).LE.0.0) GO TO 129
      G(N,X)=0.0
129   CONTINUE
      WRITE(6,173)
173   FORMAT(/5X,'THE TABLE OF EXPECTED RETURN'/)
      WRITE(6,*)((G(I,X),X=1,K),I=1,8)
```

```
C77   FORMAT(8(20F7.2/))
      KP1=K
      DO 11 X=1,KP1
      N=8
      F(N,X)=G(N,X)
      D(N,X)=(X-1)
11    CONTINUE
      I=N-1
3     X=1
      F(I,X)=G(I,1)+F(I+1,1)
      D(I,X)=0
      DO 5 X=2,KP1
      F(I,X)=G(I,1)+F(I+1,X)
      D(I,X)=0
      DO 5 Z=2,X
      IF (G(I,Z)+F(I+1,X-Z+1).LE.F(I,X)) GO TO 5
      F(I,X)=G(I,Z)+F(I+1,X-Z+1)
      D(I,X)=(Z-1)
5     CONTINUE
      IF (I.EQ.1) GO TO 6
      I=I-1
      GO TO 3
6     XSTAR(1)=D(1,KP1)
      DO 8 I=2,N
```

```
      SUM=0
      IMI=I-1
      DO 7 J=1,IMI
      SUM=SUM+XSTAR(J)
      XSTAR(I)=D(I,KP1-SUM)
      CONTINUE
      DO 601 I=1,8
      TAR(I)=XSTAR(I)+1
      DO 601 M=1,10
      P(I,M)=U(M,I,TAR(I))
 01   CONTINUE
      WRITE(6,37) TM
 7    FORMAT(/5X,'OPT.RET.ALLO.(X-1) UNIT OF RES.TO SYS.DUR.PERI.',I3/)
      WRITE(6,*)((F(I,J),J=1,K),I=1,8)
 8    FORMAT(8(36F7.2/))
      WRITE(6,102) TM,F(1,KP1)
 02   FORMAT(/' THE OPT.RETU. DURING PERIOD',I3,' IS',F10.3/)
      RET(TM)=F(1,KP1)
      TRET(TM)=TRT+RET(TM)
      TRT=TRET(TM)
      WRITE(6,103) (I,I=1,8)
 03   FORMAT(1X,' THE OPT.ALLO. IN SUB.',8I7/)
      WRITE(6,104) (XSTAR(I),I=1,8)
 04   FORMAT(23X,8I7)
```

```
      WRITE(6,106) TM
106   FORMAT(/' THE CUR.EXP.CAPA.OF SYS. AFTER TIME',I4/)
      WRITE(6,308) (EX(I,TAR(I)),I=1,8)
308   FORMAT(8F9.2/)
      DO 310 I=1,8
      CAP(TM,I)=EX(I,TAR(I))
      DIST(TM,I)=XSTAR(I)
310   CONTINUE
1000  CONTINUE
      WRITE(6,331)
331   FORMAT(6X,'THE OPT. DIST. OF RESOURCE'/)
      WRITE(6,333) (I,I=1,8)
333   FORMAT(' T\N ',8I5,3X,'OPT.RET. ACCU.RET.OF T PER.')
      WRITE(6,335) (T,(DIST(T,I),I=1,8),RET(T),TRET(T),T=1,46)
335   FORMAT(I3,2X,8I5,F10.2,F13.2)
      WRITE(6,337)
337   FORMAT(/)
      WRITE(6,312) (T,(CAP(T,I),I=1,8),T=1,46)
312   FORMAT(I3,2X,8F6.2)
      STOP
      END
C     SUBROUTIN
      REAL FUNCTION PROB(W,Y,V)
      DIMENSION A(8),Q(10,10),B(8),P(8,10)
```

```
      INTEGER W,Y,I,J,L,T,TM,VI,V
      REAL O
      COMMON A,P,T,B,TM
      DO 3 I=1,10
      DO 5 J=1,10
      IF (J-I) 40,50,60
0     Q(I,J)=0
      GO TO 5
0     IF(I.LT.10) GO TO 15
      Q(I,J)=1
      GO TO 6
5     S=V-1
      O=I
      Q(I,J)=1-(A(Y)*(1-1/EXP(((0.01*O)**0.15)*B(Y)*S)))
      GO TO 5
0     IF(J-I-1) 70,80,90
0     GO TO 5
0     S=V-1
      O=I
      Q(I,J)=A(Y)*(1-1/EXP(((0.01*O)**0.15)*B(Y)*S))
      GO TO 5
0     Q(I,J)=0
5     CONTINUE
3     CONTINUE
```

```
 6      IF (W.GT.1) GO TO 99
        IF (TM.NE.6) GO TO 99
        VI=V-1
        WRITE(6,81) Y,VI
81      FORMAT(5X,'TRAN.MATRIX IN SUBSYS.',I3,'  WITH RESOURCE',I4)
        WRITE(6,91)((Q(I,J),J=1,10),I=1,10)
91      FORMAT(/10(10F7.4/))
99      PROB=0
        DO 685 L=1,10
685     PROB=PROB+P(Y,L)*Q(L,W)
400     RETURN
        END
```

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