COMPUTER SIMULATION OF LIFELINE RESPONSE TO EARTHQUAKES

by

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SYNOPSIS

A method is described for using digital computer simulation to evaluate the response of lifelines to earthquakes. Information gained from the simulation enables seismic specifications of equipment and facilities to be evaluated in a system context. This capability is of particular importance for power, communication and other lifeline systems since these systems are highly redundant. Information is also gained on improving the post-earthquake recovery process. While the general methodology could be applied to all ground-based lifelines, parts of the computer code of the simulation are tailored to model electric power systems.

INTRODUCTION

The importance of power, water, transportation, communication and waste removal systems to a modern industrialized society in a post-earthquake environment cannot be overemphasized. The San Fernando earthquake of 1971 demonstrated that a moderate-sized earthquake can cause significant damage to these systems (1,2). This experience raised the technical community's awareness of lifeline vulnerabilty and provided detailed information about the earthquake response of specific lifeline equipment and facilities. Also, efforts were directed at determining the resistance of individual pieces of equipment and facilities through testing and analysis. While this activity continues, it is at an ever-slower rate as the time since the last damaging earthquake increases. As a result of this effort, many lifeline companies have adopted or increased the seismic specifications for their equipment and facilities.

Most lifelines, to a degree, and power and communication systems in particular, present a unique problem in determining the effect of improved earthquake resistance of individual equipment on system reliability. Due to the importance of these systems and the impossibility of making each element failure-proof, they are designed to be highly redundant. Thus, since the effects of these modifications have not been evaluated from a systems point of view, it is not clear if the improvements which have been instituted are cost-effective, necessary or adequate to prevent significant disruption from future large earthquakes. Interviews with engineers involved in earthquake design indicate that the passage of time since the San Fernando earthquake and recent economic pressures have made decision makers who allocate resources reluctant to spend more on earthquake mitigation. This also suggests the need for a methodology to show whether such expenditures are cost-effective.

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While the earthquake resistance of structures and equipment can be improved so as to reduce the disruptive effects of earthquakes, this cannot be done without increased costs. These costs include not only the increased economic costs of the facilities themselves and the administrative costs which would be required to ensure that standards are met, but also non-economic costs associated with the imposition of added restraints to complicate human life. Both the size and character of the economic and non-economic costs associated with providing earthquake resistance suggest that decisions concerning the desired degree of earthquake resistance rest with the public itself through its representatives and are beyond what is appropriate for the technical community to determine on purely technical grounds. Thus, the technical community must not only establish and meet the specifications to satisfy the public policy for earthquake resistance, they must also determine and communicate to the public in meaningful and useful terms the information it needs to establish public policy.

The approach described here considers the vulnerability and response of lifelines to a specific hypothesized seismic event. While more than one event can be considered and the statistics of a series of events collected and evaluated, the lifeline response is studied in detail on an event-by-event basis. The distinction between risk analysis and the evaluation of vulnerability and system response should be noted. Vulnerability analysis, as described below, considers the lifeline in detail. Each major piece of equipment, or group of closely related pieces, is considered individually, then the individual failures are combined to evaluate total system performance. Also, the period following the earthquake is modeled so that the repair process and duration of disruption can be evaluated.

The general approach to vulnerabilty analysis is through the integrated use of deterministic models, Monte Carlo methods and discrete event simulation on a digital computer. The essence of the Monte Carlo method is to perform several replications of the simulation, varying certain parameters according to known probability distributions. Discrete event simulation is one approach to the modeling of a process which advances through time. In this approach the process is characterized in terms of "events" which denote changes in the state of the system. Time is advanced discretely from one event to the next.

The structure of the simulation is described in the next section of the paper. Following that is a description of the power system case study.

STRUCTURE OF THE SIMULATION

The structure of the simulation must be viewed from two perspectives. First, the logical structure is comprised of the relationships of earthquake effects to equipment damage and equipment damage to the performance of each lifeline, and includes the interaction between lifelines. The logical structure is modular, as shown in Figure 1, with further modularity within each lifeline module. Each module is self-contained except at the required interfaces where interaction is well-defined.

A second structure associated with a lifeline simulation is that of the actual computer code. Judicious structuring is necessary in order to effectively handle a large-sized simulation. While calculations are rela-simple and executed rapidly, the problems of data management can be overwhelming. For example, in the simulation of an electric utility described below, over 300,000 items of information are required to describe the system, each of which must be organized so that it can be associated with a specific piece of equipment and related to other pieces of equipment. The data management problem has two facets. The first is the problem of size so that information can be stored and recovered when needed. The second, and more difficult, problem is the speed of the data recovery process in the course of the simulation. As a result, data must have two separate organizations, one for data entry and one for simulation use. The details of the solution to this problem will be described elsewhere.

ELECTRIC POWER SYSTEM CASE STUDY

The development of a methodology to simulate the earthquake response of a lifeline was done in conjunction with a real electric power network in a major metropolitan area. Some significant advantages were thus gained. A large system was selected, since the data management problem was a vital part of the methodology and had to be solved if the methodology was to be generally applicable. Further, real power systems present problems which would not be addressed if a hypothetical system was utilized. For example, since a power system has evolved over the life of the city, equipment design, methods of construction, and equipment configurations change and should be accounted for in the analysis of the system. Close interaction with the utility also provides resource people who can assist in making various assumptions and simplifications required to make the simulation more manageable while yielding results which are credible.

The logical structure of the power system simulation is shown in Figure 2. Each module is briefly described below; detailed analyses are to be presented elsewhere. The calculations performed in the first four modules are done once for each seismic event. The results of these calculations may be repeatedly used in the Monte Carlo simulation, which is contained in the next four modules, those enclosed by dotted lines in Figure 2. Additional details of the Seismic Event, Local Seismic Environment, Equipment Vulnerability, and Equipment Damage modules are presented elsewhere (3).

Seismic Event. From information on the geology, seismicity, and history of previous earthquakes affecting the study area, a number of possible earthquakes associated with faults in the area are postulated. Each fault may have several different earthquakes associated with it, one corresponding to the estimated maximum possible magnitude for that fault and several of lesser magnitude in which a smaller portion of the fault would release energy. The choice of particular rupture locations along the length of the fault is made by viewing the fault location in relation to the geographical configuration of the power system. For each run of the simulation, a single fault, magnitude, and rupture location are hypothesized.

Local Seismic Environment. Given the magnitude and location of the active part of the fault, the local seismic environment for each equipment site is evaluated. Existing propagation attenuation and subsoil amplification laws are used to obtain peak values of the acceleration, velocity and displacement along with a surface ground motion spectrum which incorporates local site conditions. Methods for dealing with the distributed character of the fault are incorporated.

Equipment Vulnerability. The seismic exposure of each piece of equipment is determined from knowledge of its dynamic characteristics and mounting and the local seismic environment at its site. The "equipment damage parameters" used to express seismic exposure are the peak acceleration, velocity, and displacement. These parameters are used in the Monte Carlo part of the simulation as described later.

Post-Earthquake Power Demand. Since few types of equipment other than electrical power equipment must meet seismic specifications an earthquake which damages power equipment will do even more damage to non-power facilities and operations. Thus, power demand after a damaging earthquake will be lower than under normal conditions. The extent of demand reduction following the earthquake is found by relating users' disruption to the severity of ground motion at the substation providing them with power. A pattern estimated from past earthquake data is used to increase demand toward its normal level with the passing of time.

Equipment Damage. The Monte Carlo simulation is initiated in this module. For each Monte Carlo run, the status of every piece of equipment within the system is determined. Each mode of failure, that is, each way in which each piece of equipment may be damaged, has been identified and represented by a fragility curve. From this curve an equipment damage parameter determines the probability of failure in that mode. A random number generator and the probability of failure are used in a test to determine whether the equipment fails in that mode. The modes of failure also provide information on the resources (men, materials and equipment) required to repair or replace the damaged equipment.

Power System Reconfiguration. To measure the actual disruption of service, it is necessary to determine whether the damaged system can meet the post-earthquake power demand. This is done by rerouting the power within the system in conjunction with load flow analyses. In this reconfiguration, a loss function is optimized which takes into account the number and duration of customer disruptions, and the level of service customers are getting. The effect of restoring particular items of damaged equipment is also determined.

Recovery. Given the information on effects of specific repairs, priorities for repairs are established on a cost/benefit basis, subject to the availability of spare parts, men, and support equipment. The recovery process is modeled for a simulated period of several days to weeks. This module is comprised of a discrete event simulation, encompassing the allocation of manpower and spare parts and the repairing of specific items of equipment.

System Performance Statistics. For each of the Monte Carlo runs, statistics are gathered on the number, duration and spatial distribution of customer disruptions, and on the type and spatial distribution of equipment damage.

By reinitializing the system and generating a different set of random numbers it is possible to evaluate another response of the system to the same earthquake.

System Performance Evaluation. By evaluating the system response to different Monte Carlo runs and to different earthquakes a measure of system performance can be obtained.

Using the simulation the effects on system performance of changed equipment specifications could be evaluated. Also, the persistent recurrence of patterns of damage would indicate weaknesses in system configuration.

CONCLUSIONS

The importance of lifelines, both in terms of the services which they provide and their cost, requires that their performance be adequate following large earthquakes and that unnecessary expense associated with their over-design be avoided. The economical design of equipment and facilities associated with lifelines requires that the highly redundant character of these systems be taken into account in establishing seismic specifications. The difficulty in the evaluation of seismic specifications does not obviate the need for decision makers to have a sound basis for allocating resources to improve earthquake resistance. The simulation methods which have been described here provide a tool to aid in this evaluation. The methodology can also provide information to form a basis for establishing public policy on the degree of earthquake resistance which is desirable.

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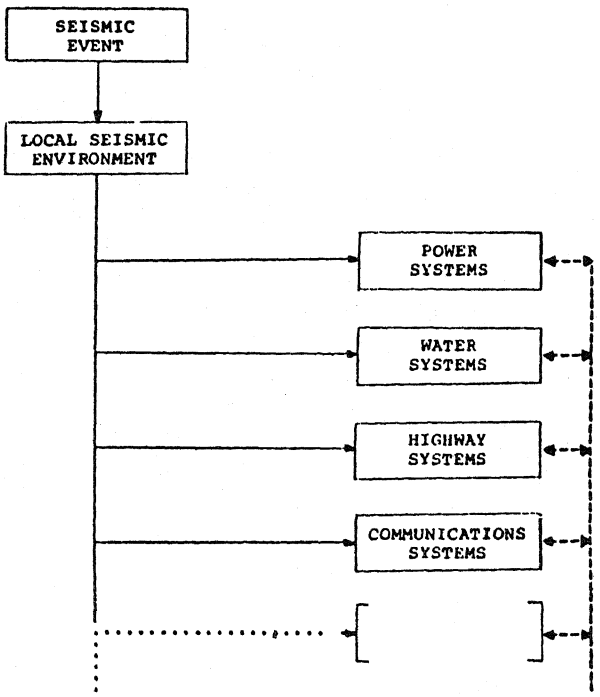

Figure 1

Logical Structure for Simulation of Lifelines

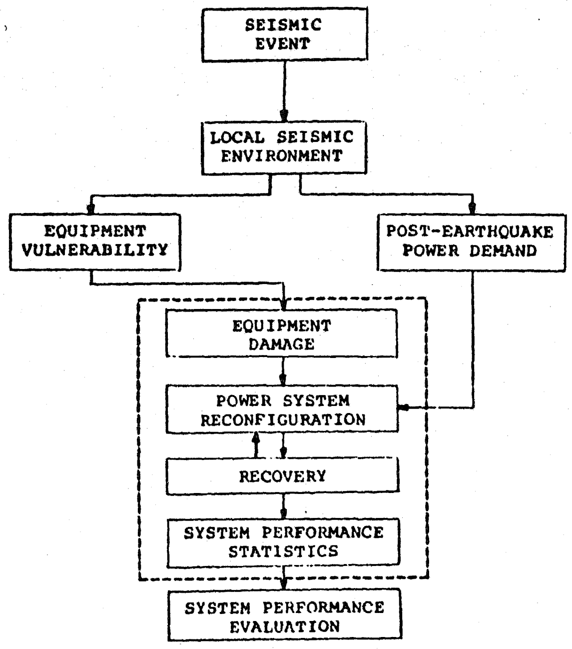

Figure 2

Logical Structure of Power System Simulation