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EFFECTS OF LIFELINE INTERACTION UNDER SEISMIC CONDITIONS

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ABSTRACT

Lifeline system interactions have been suggested to occur and indeed have often been observed under earthquake conditions, particularly under severe ones. Indeed, the January 17, 1995 Hyogoken-Nambu earthquake (Kobe Earthquake) showed that lifeline system malfunctions and interactions can severely impede the post-earthquake emergency response and delay the earthquake disaster mitigation process. This paper presents an analysis of such interactions that might occur between water delivery and electric power transmission systems subjected to a scenario earthquake. In doing so, the internal system redundancy of substations is taken into consideration. The basic data to describe physical characteristics of these lifeline systems are provided by MLGW (Memphis Light Gas and Water) Division, Memphis, Tennessee.

KEYWORDS

Lifeline System; Water System; Electric Power System; System Interaction; GIS.

INTRODUCTION

It is well known that the performance of a lifeline system during and following a severe earthquake depends on the seismic performance of other lifeline systems serving the same general urban or regional communities. Considering, for example, a water delivery system, its pumping stations, if not equipped with in-house emergency electric power generators (typically diesel engine-based), cannot function when the supply of electric power is interrupted as a result of the failure of the electric power transmission system due to a severe earthquake. Another example is the transportation lifeline system, typically a highway network whose functional failure significantly impedes post-earthquake emergency repair operations for all lifeline systems including itself. In this case, the functional failure results from the seismic damage sustained by its structural components such as embankments, bridges and road surface pavement, and/or from the debris on the road surface generated, for example, by damaged buildings along the roads and streets, which make the highways, roads and streets impassable. Such impassability also affects the mobility of fire-engines and thus seriously degrades the post-earthquake fire-fighting capability of the water delivery system. In fact, the January 17, 1995 Hyogoken-Nambu earthquake provided textbook examples of these and other lifeline system interactions.

The performance interaction of lifeline systems under earthquake conditions was studied earlier by many authors including Hoshiya and Ohno (1985), Nojima and Kameda (1991), and Scawthorn (1992). The present paper further extends the scope of the earlier work by these and other authors and performs a quantitative analysis through which the performance interaction between an electric power transmission and a water delivery system is evaluated. Such a quantitative analysis is extremely useful in identifying and prioritizing important performance parameters of the lifeline systems involved (such as the fragility curves of substations of the electric power system) for the retrofitting purposes.

In the following, numerical results are obtained using analytical models of electric transmission and water delivery systems developed on the basis of the corresponding Memphis systems. These are not exact models of the Memphis systems due to the unavailability of complete information, although the models developed are expected to represent approximately the physical characteristics of the Memphis systems. In this regard, caution must be exercised if the numerical results obtained are to be used for the purpose of deriving specific technical and operational recommendations for the Memphis systems.

ELECTRIC POWER SYSTEM

Conditions for System Failure

MLGW's electric power transmission network is depicted in Fig. 1. It transmits electric power provided by TVA (Tennessee Valley Authority) through gate stations to 45 substations in the network consisting of 500kv, 161kv, 115kv and 23kv transmission lines and gate, 23kv and 12kv substations. The 500kv line and gate stations are operated by TVA, while other transmission lines and substations by MLGW. Each substation is associated with a service area, and usually one service area is served by only one substation except for two occasions.

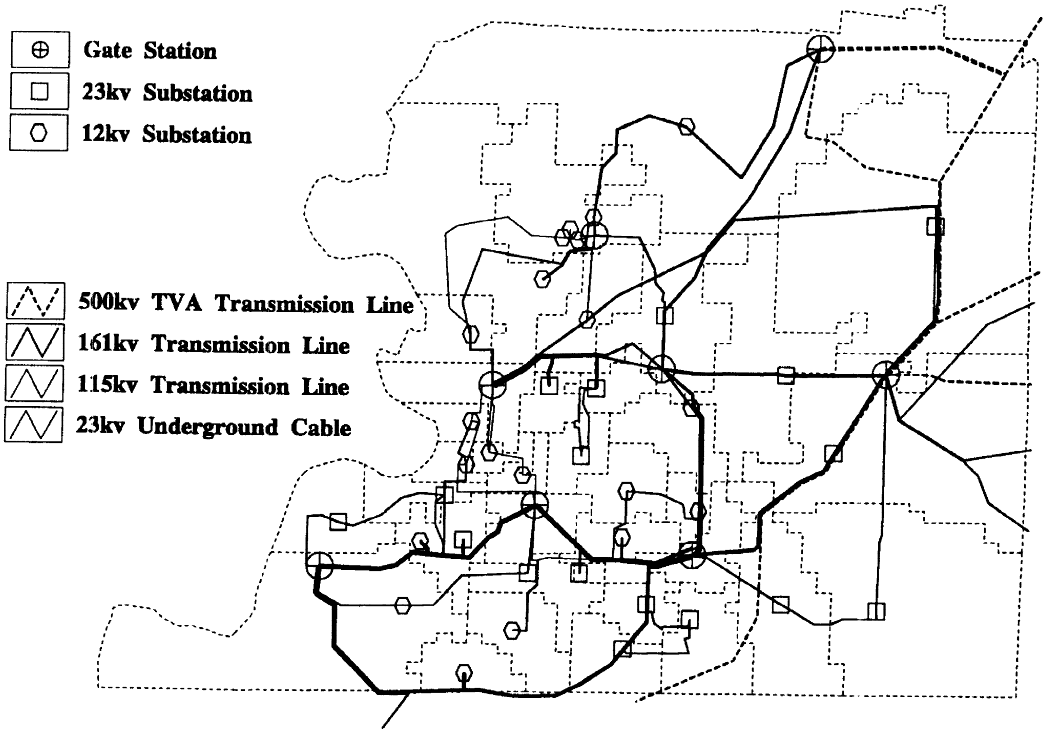


Fig. 1 MLGW's Electric Power Transmission Network

In analyzing the functional reliability of each substation, the following modes of failure are usually taken into consideration; (1) loss of connectivity, (2) failure of substation's critical components, and (3) power imbalance. Each of these failure modes is taken into consideration in this paper. However, it is noted that most of the transmission lines of the MLGW system are aerial supported by transmission towers. While by no means this implies that the transmission lines are completely free from seismic vulnerability, it is assumed in this study that they are, primarily for the purpose of analytical simplicity.

Substation Model

An electric substation consists of several electric nodes subjected to various values of voltage and connected each other through transformers in order to reduce the voltage and/or distribute the power to the service areas. Each electric node consists of many kinds of electric equipment such as buses, circuit breakers, and disconnect switches. The schematic diagram of an actual MLGW's substation is provided by MLGW and used to model the substations. Among the equipment, buses, circuit breakers and disconnect switches are seismically most vulnerable, as observed during the 1971 San Fernando, the 1989 Loma Prieta and the 1994 Northridge earthquake (Benuska 1990; Hall 1994; Goltz 1994).

The physical damage thus sustained by the system produced corresponding system malfunction that required concentrated repair and restoration effort to make them operational again. However, in spite of the damage, the system performed reasonably well on the occasions of these earthquakes. Two factors played a significant role in this respect. First, the high voltage power transmission network is designed topologically with a sufficient degree of redundancy in transmission circuits, which makes it easy for system operators to respond to emergency situations. Second, substations are designed also with a sufficient degree of internal redundancy. Actual equipment configuration in a node is so complicated that it defies a rigorous modeling. Therefore, a simplified configuration as shown in Fig. 2 is employed. In Fig. 2, if only one circuit breaker CB11 is damaged due to an earthquake, the node is still functional because all the lines remain connected each other. However, if CB11 and CB13 are damaged simultaneously, Line A and Line B are disconnected from the node, thus the function of the node is impaired. This indicates the nature of substation system redundancy.

Utilizing the results of the previous studies by Shinozuka et al. (1989) and Ang et al. (1992) the fragility curve $F_c(a)$ for a circuit breaker is chosen to be a log-normal distribution function with the median and coefficient of variation equal to 0.45g and 0.38 respectively. This curve is assumed also applicable for the bus fragility for the purpose of simplicity.

Monte Carlo Simulation

Utilizing the GIS (Geographical Information System) (ESRI, 1988; Sato et al., 1991) capability existing at the University of Southern California, the map of the electric transmission network is overlaid with the map of PGA identifying the PGA value associated with each substation under each scenario earthquake. The fragility curve developed for the equipment (buses and circuit breakers) can then be used to simulate the state of equipment damage involving the equipment in all the nodes at all the substations of the transmission system. For each damage state, the connectivity and flow analyses are performed with the aid of an computer code IPFLOW developed and distributed by Electric Power Research Institute (EPRI) (1992).

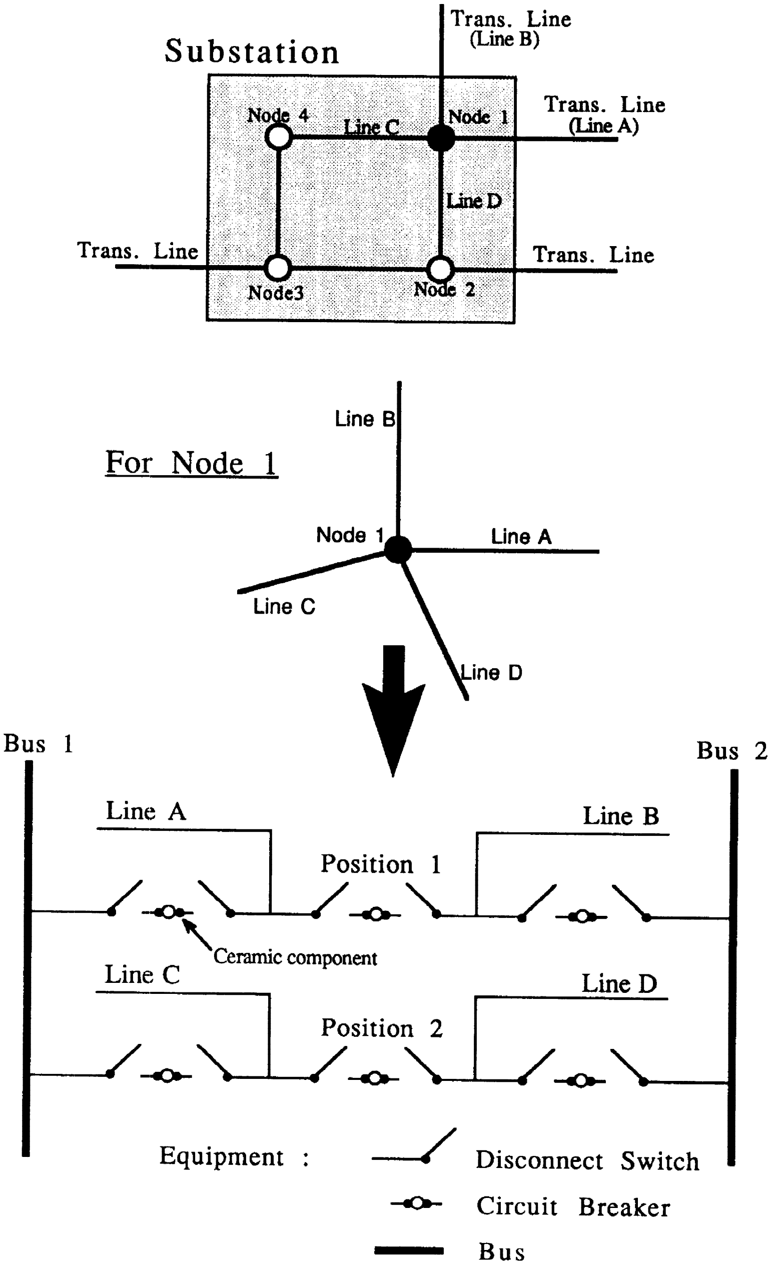
The loss of connectivity occurs when the node of interest survives the corresponding PGA, but is isolated from all the generating nodes because of the malfunction of at least one of the nodes on each and every possible path between this node and any of the generating nodes. Hence, the loss of connectivity with respect to a particular node can be confirmed on each damage state by actually verifying the loss of connectivity with respect to all the paths that would otherwise establish the desired connectivity. The loss of connectivity is primarily due to the equipment failure not only at the node of interest but also all other nodes in the network.

As to the abnormal power flow, it is noted that the electric power transmission system is highly sensitive to the power balance and ordinarily some criteria are used to judge whether or not the node continues to function immediately after internal and external disturbances. Two kind of criteria are employed at each node for the abnormal power flow; (a) power imbalance and (b) abnormal voltage. When some nodes in the network are damaged due to an earthquake, the total generating power becomes greater or less than the total demanding power. For a normal condition, the power balance between generating and demanding power is in a certain tolerance range. Actually, the total generating power must be between 1.0 and 1.05 times the total demanding power for normal operation even accounting for the power transmission loss.

If this condition is not satisfied, the operator of the electric system must either reduce or increase the generating power to keep the balance of power. However, in some cases, supply cannot catch up with demand because the generating system is unable to respond so quickly. In this case, it is assumed that the generating power of each power plant cannot be quickly increased or reduced by more than 20% of the current generating power. When the power balance cannot be maintained even after increasing or reducing the generating power, the system will be down. This kind of outage is defined as a power imbalance. This situation, however, has never materialized in our analysis for the MLGW system.

As for the abnormal voltage, voltage magnitude at each node can be obtained by power flow analysis. Then, if the ratio of the voltage of the damaged system to the intact system is out of a tolerable range (plus/minus 20% of the voltage for the intact system), it is assumed that a black out will occur in the area served by the substation.

For the Monte Carlo simulation under a scenario earthquake with M=7.5 epicentered at Marked Tree (see Fig. 3), each substation is examined with respect to its possible malfunction under these three modes of failure for each simulated damage state. Thus, each simulation identifies the substations that will become inoperational.



Note that disconnect switches are normally closed

Fig. 2 Typical Node Configuration Model

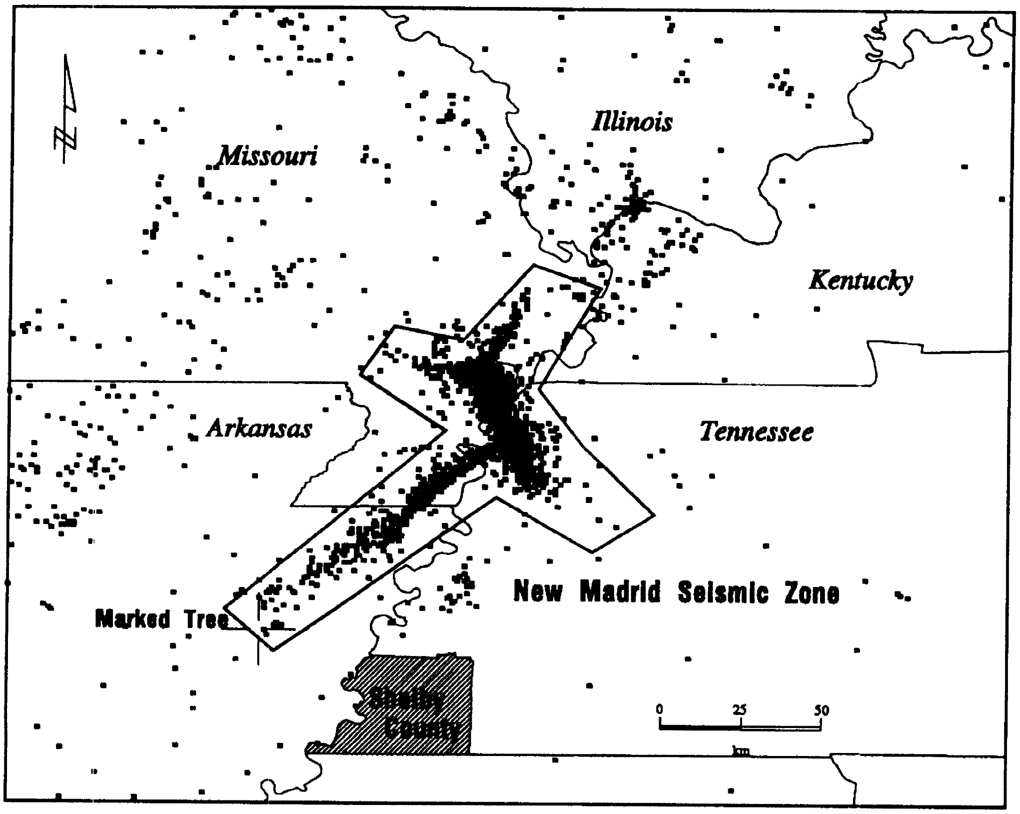


Fig. 3 Scenario Earthquake Epicenter (Marked Tree)

SYSTEM INTERACTION

A seismic reliability analysis method based on Monte Carlo simulation techniques was developed for water delivery systems by Shinozuka et al (1992) and further improved by Tanaka et al (1993) without, however, taking into consideration the effect of interaction with the electric power system into consideration. The method was used in estimating the seismic reliability of the MLGW's water delivery system as shown in Fig. 4 where the location of pumping stations and booster pumps are also indicated.

Taking advantage of the versatility of the Monte Carlo simulation technique and employing the same fragility information used in Shinozuka et al (1992) on the component facilities of the water delivery system, the damage state of the water system is also simulated each time the damage state of the electric power system is simulated under the same scenario earthquake. The component facilities to the water system included for fragility consideration are pumping station, booster pumps, elevated tanks and pipelines.

If the system interaction is not considered, Fig. 5 is obtained indicating the seismic performance of the water system where the average output flow (in each census tract) for the damaged network is plotted. The average is taken over the entire sample of size equal to 100. In reality, however, the pumping stations and booster pumps in an electric service area will be out of action when the substations supplying the electric power to the service area become inoperational due to seismic impact. This probability must be and in fact has been accounted for in the present Monte Carlo simulation analysis thus taking the system interaction into considered. Fig. 6 shows the result of the analysis with the system interaction considered. Comparison between Figs. 5 and 6 clearly indicates the degrading effect of interaction when the impact of malfunction of substations is incorporated into the analysis.

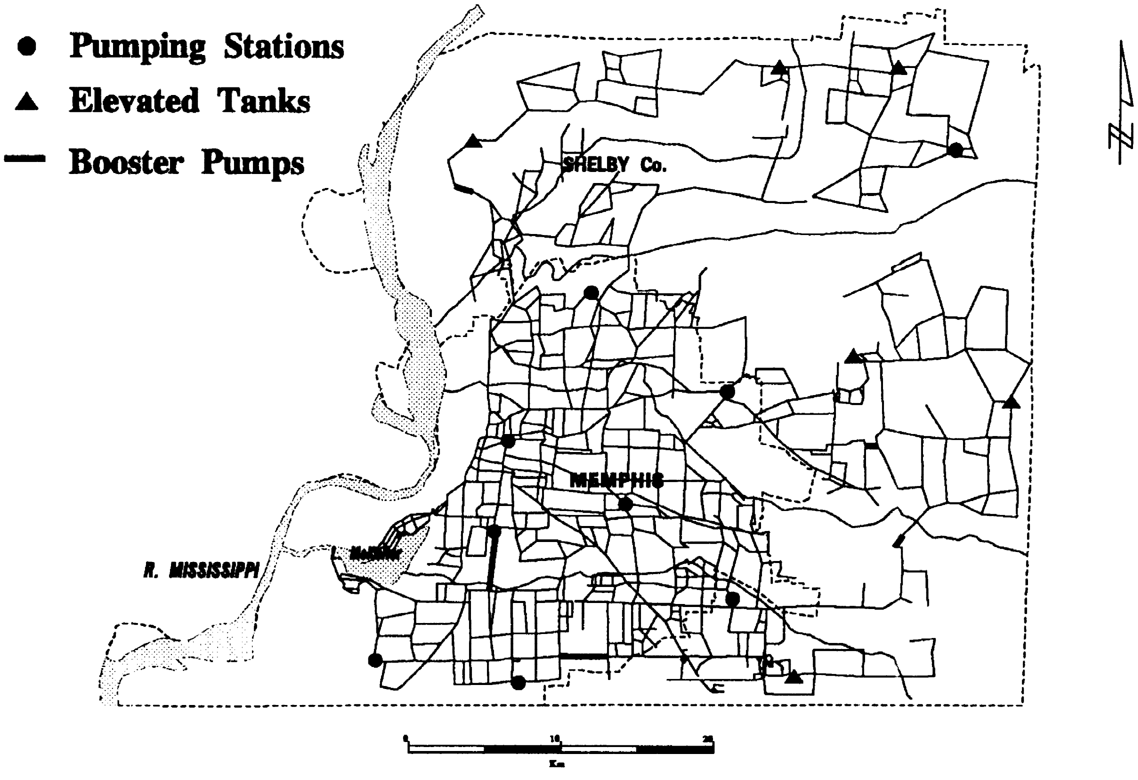


Fig. 4 MLGW's Water Delivery Network

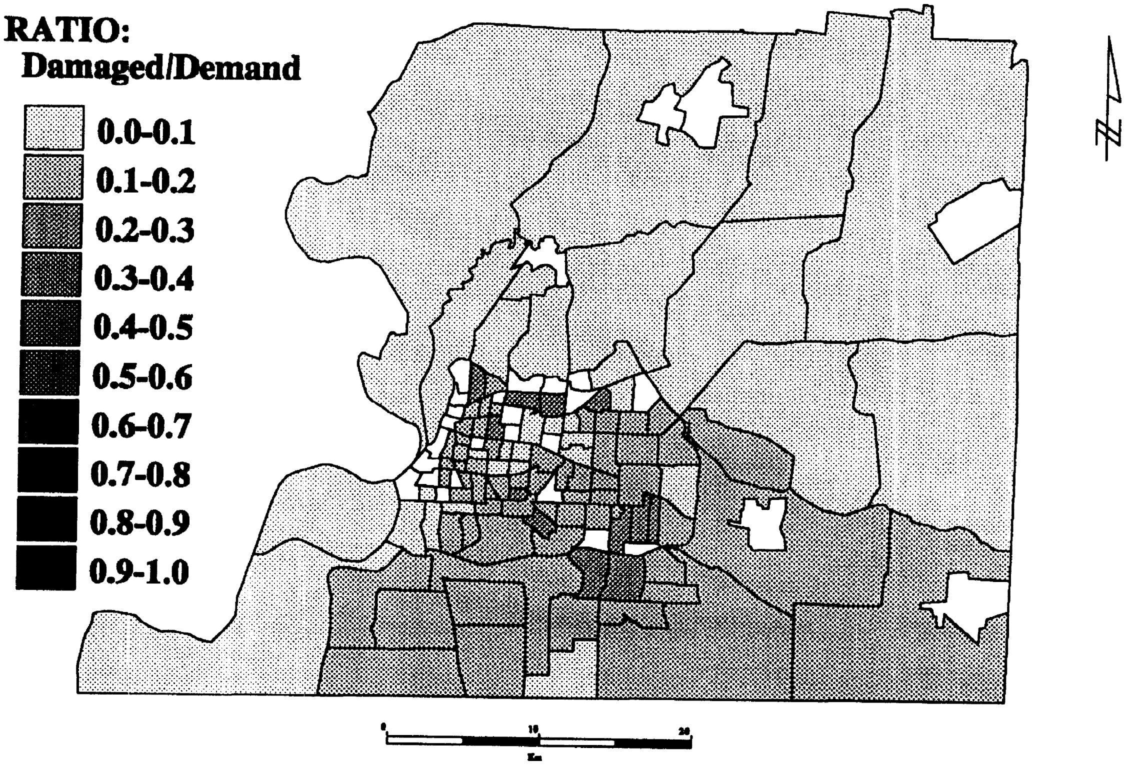


Fig. 5 Ratio of Output Flow between Intact Demand and Damaged Condition in Census Tracts without System Interaction Effect

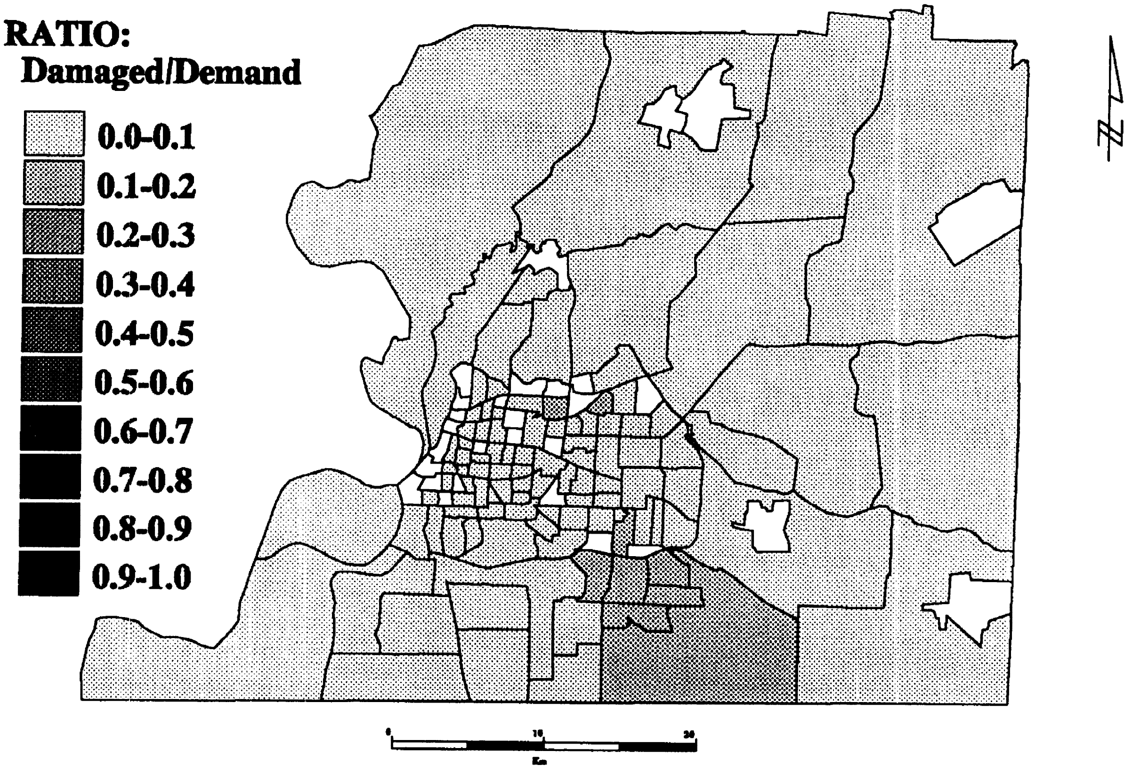


Fig. 6 Ratio of Output Flow between Intact Demand and Damaged Condition in Census Tracts with System Interaction Effect

CONCLUDING REMARKS

The analytical models are derived from the physical and operational data provided by Memphis Light, Gas and Water Division of Memphis, Tennessee, for its electric transmission and water delivery systems. The interaction effect of these two systems under a scenario earthquake is evaluated as quantitatively as possible on the basis of these analytical models. The numerical example utilizing Monte Carlo simulation techniques clearly indicates the degrading performance of the water delivery system due to the interaction effect between these two systems under the secnario earthquake considered. In the numerical example, the interaction is assumed to materialize when the malfunction of substations interrupting the supply of electric power renders pumping stations and booster pumps of the water delivery system inoperational. Finally, it is noted that this paper represents a revised version of Shinozuka et al (1994) accounting for substation redundancy and as such contains common materials.

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