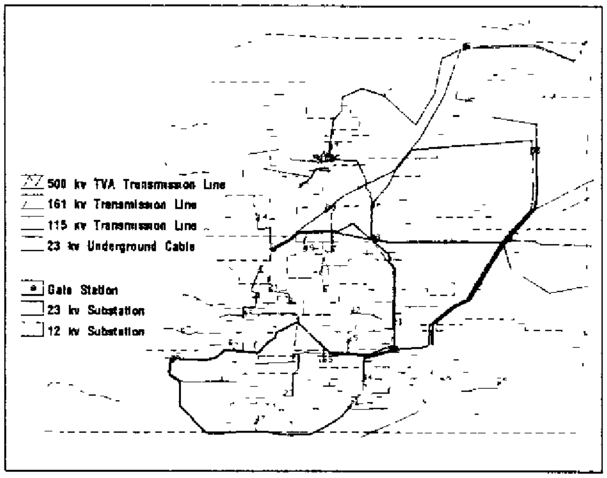
tion (Shinozuka, et. al., 1992) permits the county and city officials to estimate the shortage of potable water for each census tract immediately after the scenario or similar earthquakes, and possibly more importantly, the degradation of post-earthquake firefighting capability of the system Depending on the information thus obtained, officials can make a preparedness plan for hauling the water for human consumption from neighboring undamaged areas and also start working on the improvement of facilities to ensure that firefighting capabilities be kept above the acceptable level under the scenario earthquake. Other plausible scenario earthquakes must be considered for future earthquake preparedness.



■ **Figure 4**
MLGW's Electric Power Transmission Network

Interaction Analysis of Lifeline Systems

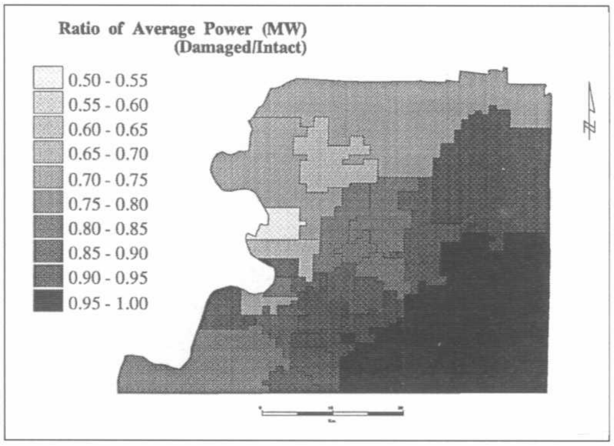
Lifeline system interactions have been suggested to occur and indeed have often been observed under earthquake conditions, particularly under severe events. An analysis of interactions that might occur between water delivery and electric power transmission systems subjected to the scenario earthquake have been performed as part of this study. In carrying out this analysis, however, some of the basic data to describe physical characteristics of the water delivery and electric power transmission systems of MLGW were not available and hence were simulated. In view of this, the result of this analysis, although the first of its kind in quantitative details, must be interpreted accordingly.

Electric Power System

Conditions for System Failure: MLGW's electric power transmission network is depicted in figure 4 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 are operated 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.

In analyzing the functional reliability of each substation, the following modes of failure were taken into consideration; (1) loss of connectivity, (2) failure of substations and (3) power imbalance Each of these failure modes was addressed in the analysis from the viewpoint of the ensuing reliability analysis of the MLGW's electric power transmission system. Specifically, the most current information on the fragility curves was used for the substation.

Monte Carlo Simulation: Utilizing the GIS capability existing at Princeton University, a map of the electric transmission network was overlaid with the map of PGA identifying the PGA value associated with each substation With the aid of the fragility curves developed earlier, this determined the probability of each substation to malfunction under the PGA identified. Monte Carlo simulation was then carried out to generate a large number of states of damage for the transmission system Each damage state represents one of 2^{M} damage states in which M' specific substations malfunction and other M - M' substations function ($M' = 0, 1, ... M$). For each damage state, it can be determined whether or not a substation malfunctions due to a loss of connectivity. The loss of connectivity occurs when the substation of interest survives the corresponding PGA, but is isolated from all the gate stations because of the malfunction of at least one of the substations on each and every possible path between this substation and any of the gate stations. Hence, the loss of connectivity with respect to a particular substation 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. This is an easy task, particularly when the network is as simple as considered in this study. It can also be determined whether or not a substation malfunctions due to the corresponding PGA. In fact, each simulated state of damage explicitly provides this information.



■ **Figure 5**
Ratio of the Average Power [MW][Damaged/Intact]

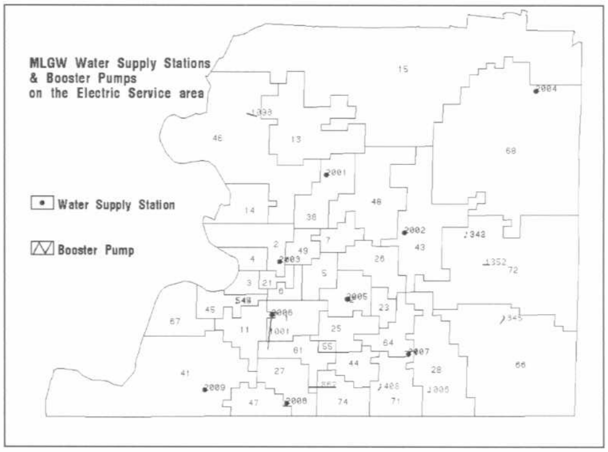
Finally, the malfunction of a substation due to power imbalance was confirmed by carrying out the flow analysis with respect to the network in each damage state. A special computer code was used for this purpose.

Each substation was examined with respect to its possible malfunction under these three modes of failure for each simulated damage state. In the present study, a sample of size of 100 was considered for the Monte Carlo analysis. The probability P_{Em} of malfunction of a particular substation m is then estimated as $N_m/N = N_m/100$, where N_m is the number of simulated damage states in which the substation m malfunctions in at least one of the three modes. On the basis of the flow analysis performed on the network in 100 simulated damage states, the ratio of the average electric power output (real-power in MW) of the damaged network to that associated with the intact network was computed and plotted in figure 5. The ratio is a convenient measure to show the degradation of the system performance due to the earthquake. The average was taken over the entire sample of 100.

System Interaction

The effect of the performance degradation of the electric power transmission system on the water delivery system serving the same regional community was analyzed using the electric power transmission and water delivery system operated by MLGW as an example.

Figure 6 shows a map of the electric power service areas together with the locations of the pumping stations and booster pumps of the water delivery system. For the numerical analysis,



■ **Figure 6**
MLGW's Water Supply Station on the Electric Service Area

it was assumed that the pumping stations and booster pumps in a service area ceased to operate due to the lack of electric power if all the substations serving that service area malfunction. In the earlier study performed by Hwang et al. (1992), the fragility curve of a pumping station in the MLGW's water delivery system was estimated. Hence, the probability of a pumping station to malfunction under the scenario earthquake could also be estimated. If, therefore, this pumping station is located in the service area served by the substation, then the probability of the pumping station to malfunction can be written as:

$$P_j = 1 - (1 - P_{uj})(1 - P_{Em}) \cong P_{wj} + P_{Em}$$

where the approximation is valid when both P_{uj} and P_{Em} are small compared with unity. Appropriate modifications can be made to estimate the probability of malfunction of a pumping station located in the service area served by more than one substation. The probability of a booster pump to malfunction is equal to the probability P_{Em} if the pump is located in the service area served by substation since, in the earlier analysis performed by Shinozuka et al (1992), the pumping stations were assumed not to be seismically vulnerable. This same analysis was repeated with the added probability of malfunction for pumping stations and booster pumps due to the malfunction of electric power substations. Figure 7 shows the average water head and output flow rate at each demand node of the damaged water delivery network and their ratios to the corresponding values of the undamaged network. Figure 7 clearly indicates the degrading effect of interaction when the impact of malfunction of electric power substations was incorporated into the analysis.

Repair and Restoration

The post-earthquake restoration of a water delivery system is a critical issue to be seriously addressed. In an earlier approach for optimum

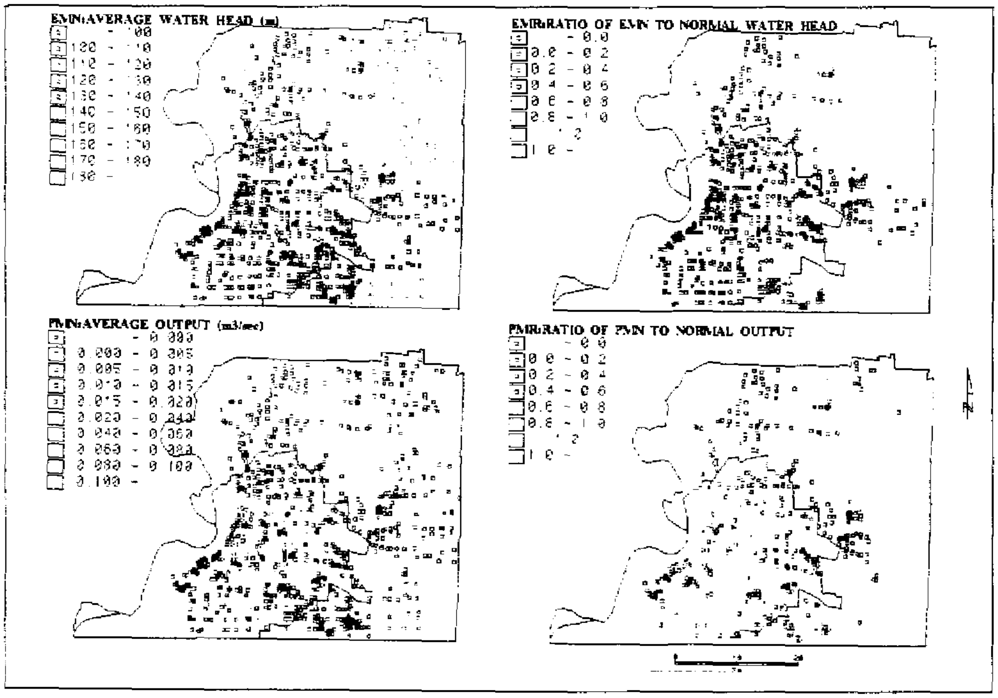
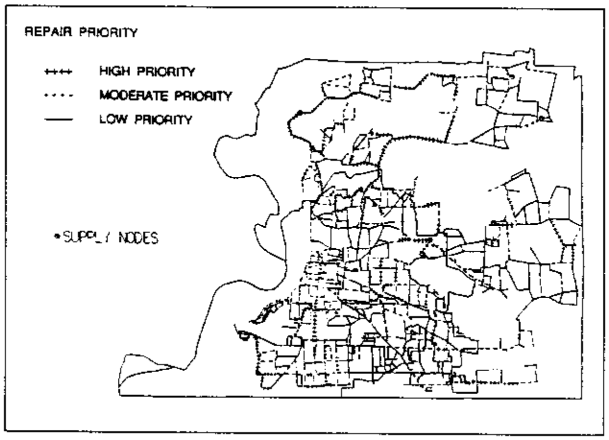


Figure 7

Water Head Under Damaged Condition (Interaction Considered)

temporary restoration of a seismically damaged water network developed by Shinozuka et al. (1993).a short-route network was first established by determining the shortest route from each demand node to the nearest supply node. The links not included in the short-route network were excluded from temporary repairing. The priority for repairing a link was determined on the basis of two factors: the necessity of repair and the easiness of repair. The easiness of repairing a link depends on the number of breaks in the link, while the necessity of repair depends on the degree of water shortage and the number of customers associated with the link.

These flow parameters obtained by damaged condition analysis were used to determine the necessity of repair and the easiness of repair for each link. On the basis of these two factors, the priority for repairing each link was then established (figure 8). The links closer to the supply nodes have a higher priority for restoration. In addition, many links in the northern part of the county also have high priority even though these links are away from the supply nodes. This is caused by severe water shortage in this area. In addition, many links within Memphis also have high priority because these links serve a large population.



■ Figure 8
Repair Priority for Temporary Restoration of the Memphis Water Network

Personnel and Institutions

The following NCEER investigators participated in the NCEER's Lifeline project. T. Ariman, University of Tulsa, D. Ballantyne, Dames & Moore (formerly affiliated with Kennedy/Jenks), C. Costantino, City University of New York, G. Deodatis, Princeton University, R. Eguchi, EQE Inc., I. Elishakoff, Florida Atlantic University, M.Q. Feng, University of California - Irvine, M.D. Grigoriu, Cornell University, M. Haroun, University of California - Irvine, H. Hwang, University of Memphis, J. Isenberg, Weidlinger Associates, M. O'Rourke, Renssalaer Polytechnic Institute, T. O'Rourke, Cornell University, A. Schiff, Precision Measurement Instruments, M. Shinozuka, Princeton University, and E. Vanmarcke, Princeton University.

The following investigators having expertise in Geotechnical Engineering (GE), Risk and Reliability (RR), Intelligent and Protective Systems (IP) and Socioeconomic (SE) areas collaborated with the investigators listed above in the Center's Lifeline project: Juan Benavides, (SE) Pennsylvania State University, R. Dobry, (GE) Renssalaer Polytechnic Institute, S. French, (SE) Georgia Tech, G. Martin, (GE) University of Southern California, A. Papageorgiou, (GE) Renssalaer Polytechnic Institute, J. Prevost, (GE) Princeton University, Adam Rose, (SE) Pennsylvania State University, K. Tierney, (SE) University of Delaware, and Y.K. Wen, (RR) University of Illinois

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Technical References

Burrough, P.A., "Principles of Geographic Information Systems for Land Resources Assessment," Oxford University Press, New York, New York, 1986.

Craig, E.T., "Seismic Loss Estimates for a Hypothetical Water System," ASCE Technical Council on Earthquake Engineering, Monograph No. 2, American Society of Civil Engineers, New York, 1991.

Environmental Systems Research Institute (ESRI) "ARC/INFO Users Manual," Environmental Systems Research Institute, Redlands, California, 1989.

Hwang, H., Ch'ng, A., and Hsu, H., "Seismic Fragility Analysis of Memphis Sheahan Pumping Building," Technical Report, Center for Earthquake Research and Information, Memphis State University, 1992.

Hwang, H., Lee, C.S., and Ng, K.W., "Soil Effects on Earthquake Ground Motions in the Memphis Area," Technical Report NCEER-90-0029, National Center for Earthquake Engineering Research, University at Buffalo, August 2, 1990.

Iwasaki, T., Tatsuoka, F., and Takagi, Y., "Dynamic Shear Deformation Properties of Sand for Wide Strain Range," Report of Civil Engineering Institution, No. 1085, Ministry of Construction, Tokyo, Japan, 1976.

Katayama, T., Kubo, K., and Sato, N., "Earthquake Damage to Water and Gas Distribution System," Proceedings, U.S. National Conference on Earthquake Engineering, 1975, pp. 396-405.

Sato, R., Murata, M., and Shinozuka, M., "Seismic Risk Analysis of Water Delivery System Based on GIS," Proceedings, Fourth International Conference on Seismic Zonation, Stanford, California, August 25-29, 1991, Vol. III, pp. 163-170.

Shinozuka, M., Hwang, H., and Murata, M., "Impact on Water Supply of a Seismically Damaged Water Delivery System," Lifeline Earthquake Engineering in the Central and Eastern US/TCLEE Council/ASCE Sessions Proceedings, ASCE National Convention, New York, New York, September 13-17, 1992, pp. 43-57.

Shinozuka, M., Murata, M., and Hwang, H., "Restoration Planning for Memphis Water Delivery Network Based on Simulated Seismic Damage," Proceedings, 1993 National Earthquake Conference, Central United States Earthquake Consortium, Memphis, TN, Vol. I, 1993, pp. 471-480.

Tanaka, S., et al., "User's Guide for Lifeline -W (II), a Program for Connectivity and Flow Analysis of a Water Delivery System Under Intact and Seismically Damaged Conditions," Version 1, NCEER Technical Report, 1994, (to be published).