The paper focuses primarily on water supply and sewage collection systems, including pipelines, pumps and pump stations, valves, wells, control stations, tunnels, canals, aqueducts, and storage facilities. Dams, which are covered by other federal and state projects, are not addressed specifically here. Similarly, water and sewage treatment plants are complex facilities requiring special detailed studies and are not addressed specifically.

BACKGROUND

The major U.S. experience with extensive damage to water systems occurred in 1906 when the San Francisco earthquake caused the near-complete failure of the water distribution system. Essentially no water was available to fight fires immediately after the earthquake, which resulted in the conflagration of some 490 city blocks, partial damage to 32 more, $500 million damage (in 1906 dollars), and the destruction of homes for nearly 200,000 people. A total of nearly 11 square kilometers was consumed, and several days were required to bring the fires under control (Soule, 1907).

Significant, although less catastrophic, damage occurred during the 1971 San Fernando earthquake. Damage included numerous water and sewer pipeline breaks; cracking of storage tank roofs, shells, and piping; fracturing of well casings and piping; and ground failure with associated damage to reservoirs and water treatment facilities. Water supply contamination was caused by sewer damage.

Other earthquakes in the United States have caused damage to water and sewage systems (O'Rourke, et. al., 1985); however, in each instance, damage was limited enough that post-earthquake fires and disruption of water supply and sewer service did not cause widespread damage on the scale of that in 1906 or 1971. With increased population density and the aging and corrosion of water and sewage systems, however, seismic resistance and risk now constitute important issues that should be addressed in a comprehensive review of seismic preparedness.

Elements of Risk

Seismic risk involves three parts: one or more geologic hazards, the response of the system to the hazards, and the losses associated with the resulting damage, measured in dollars, deaths, or other units of loss. Evaluation of the separate components of risk involves an interdisciplinary process that requires a combination of probabilistic methods and the judgment of experienced engineers, geologists, system managers, operators, and insurance specialists.

The principal seismic hazards for water and sewage systems include ground shaking, faulting, and seismically induced ground failure, including liquefaction, slope failure, extensive cracking, differential settlement, and seismic compaction. Methods for evaluating most of these hazards are established; however, significant uncertainties exist when assigning numerical values to seismic and geotechnical parameters.

Good reviews of various related considerations are presented in American Society of Civil Engineers (1983 and 1984) and O'Rourke, Grigoriu, and Khater (1985). Data for evaluating geologic hazards can be obtained from published maps, earthquake catalogues, and several geophysical data services. Trautmann and Kulhawy (1983) outline many of these sources and explain how to obtain information from them. Additional detailed data must be obtained by field exploration and in-situ characterization of the geometry and properties of surficial deposits.

Seismic hazards then must be evaluated (in some states this may be accomplished through the seismic safety element of the state general planning requirements). The system response to the hazards then can be evaluated--including the response of individual components; the response of the network; and the response of the people in charge of operating, maintaining, and repairing the system.

Finally, to make meaningful comparisons of alternative actions, it is necessary to assign a measure of loss to various types and levels of damage. This step involves a number of technical, political, and legal issues that can have a significant effect on the applicability of the results.

Effects of Earthquakes on Water and Sewage Systems

Earthquake damage to water systems has three principal effects in the short run. First, potable water supplies to domestic and essential users (hospitals, police, emergency operations centers, etc.) may be cut off or contaminated. Second, water for firefighting may be lost. Third, water supplies to industrial facilities may be cut off. In many instances, there may be intense competition for these three uses of water, particularly the first two. Damage to sewage systems can result in loss of collection capabilities, blocked flow, or loss of pumps, causing the overflow of sewage from manholes and broken pipes and the presence of raw sewage in the streets with the associated health problems. Any quantitative measure of system performance depends on a number of criteria, such as the priority given to firefighting needs vs. potable water needs and the acceptable level of performance. A comprehensive program to reduce the risk of seismic damage to water and sewage systems requires clearly defined performance criteria that specify the required capabilities as well as the areas in which they will be needed.

MAJOR ISSUES

The seismic risk associated with water and sewage systems depends on three primary issues: optimal use of existing systems, retrofitting and maintenance of existing systems, and the seismic design of new facilities. In addition, optimization of these three functions requires a systems modeling approach--a process that itself is currently an area of active research. Finally, the performance objectives of a water or sewage lifeline system are the subject of continued technical, political, and legal debate. Each of the above five areas must be considered as an integral part of reducing risk.

Operation of Existing Systems

The success of an existing water or sewage system following an earthquake depends on many operational factors that are difficult to quantify. Prior to an earthquake, routine maintenance will determine whether the system is capable of maximum performance. Items of importance include such things as:

- Ensuring that valves can be operated (i.e., are not rusted open or shut)
- Ensuring that pumps, radios, and computers have adequate reserve sources of power
- Having an adequate stockpile and inventory of spare parts and tools, and a source of equipment and materials
- Maintaining a procedure to quickly assess damage to the system
- Maintaining a procedure to deal with the great increase in repairs required after an earthquake

Many other items contribute to the overall operation of the system. Of critical importance is the ability to isolate severely leaking portions of the water system so that reservoir capacity is not wasted. Such actions require accurate system status information and rapid, reliable response by field crews. In the 1906 San Francisco event, for example, failure of pipelines drained one city reservoir in less than 24 hours. Areas severely damaged may require temporary surface mains, and conservation must be stressed. Field repair crews must be quickly dispatched to repair critical damaged components. Overlapping personnel assignments can pay off; in the 1906 event, the Fire Chief was killed during the earthquake, and Fire Department operations were severely hampered because of the loss of his leadership (Soule, 1907).

The ability to model the system interactively can be extremely useful in allocating emergency repair efforts. This methodology has worked well in other fields. For example, oil spills in San Francisco Bay can be evaluated by a 1:1000 scale physical model of the bay maintained in Sausalito, California, by the Army Corps of Engineers; the model simulates the flows and currents in the bay so a spill can be duplicated and cleanup crews dispatched to appropriate locations to minimize contamination. Similar capabilities exist for water lifeline systems using computer graphics techniques and simulation models.

Retrofitting and Upgrading of Existing Facilities

Identification and upgrading of critical system components forms another important goal in a hazards mitigation program. Such a program requires a multidisciplinary approach and includes:

- Inspection and identification of weak components
- Evaluation of the effects of their failure on system performance
- Economic evaluation of the costs of upgrading/replacement of weak components or adding parallel, redundant pipelines, where applicable
- Setting priorities for upgrading/replacement of weak components
- Committing adequate funds for upgrading/replacement of weak components

Specific examples include anchoring equipment, replacing critical pipe segments that are badly corroded (steel) or graphitized (cast iron); repairing or replacing inoperable valves; strengthening the mountings of pumps and their water and electric or fuel lines; installing restraining glands on pipe joints likely to pull out as a result of ground shaking or permanent ground deformations (likely to be expensive for buried pipelines), and upgrading tanks to withstand higher levels of ground shaking.

New Construction

A relatively straightforward, though gradual, method of improving earthquake response is to ensure that all new construction is capable of withstanding the anticipated seismic hazards discussed previously. The hazard levels must be evaluated on a site-by-site basis, and for some specific design problems, the Uniform Building Code can be used for design. In most cases, there is limited guidance for utility engineers who must make day-to-day cost-benefit tradeoff decisions with respect to design for seismic hazards.

Modeling Water and Sewage Lifeline Systems

There are two common approaches to modeling lifeline systems: the analytical approach and the simulation approach. In their simplest form, analytical models represent a network as a set of nodes and links and evaluate continuity of flow from source to sink as a function of paths along unbroken links. Simulation models, on the other hand, represent a hydraulic network as a series of nodes and pipes and evaluate physical flow rather than continuity.

The analytical approach requires less computational effort but is limited in its flexibility for modeling the complexity of real systems. It becomes difficult to implement when continuous hazard levels and performance must be considered. The simulation approach, on the other hand, is less computationally efficient but can model a wide variety of hazards states, various component failure models, real-time behavior, and other desirable attributes using established mathematical procedures.

Performance Objectives for Water and Sewage Lifelines

Performance objectives must be specified to permit evaluation of alternative operation, repair, and construction strategies. Setting these objectives, however, depends on a number of technical, political, and legal criteria. Several example criteria are listed below:

Technical Objectives

- What are minimum potable water flow requirements?
- What are probable locations of fires and what are the associated water requirements?
- How can costs be assigned to various failures of the water and sewage systems?
- How are component vulnerabilities to be modeled: qualitatively, empirically, or analytically?
- Is an analytical or simulation approach to be used?

Political Objectives

- What are the relative priorities for health and safety vs. costs and benefits?
- What are the relative priorities for potable water vs. fire fighting vs. industrial water needs?
- What are the relative priorities for water supply and sewage collection and treatment?
- How is loss defined, and what are acceptable losses?
- How risk-averse is the public, and how much earthquake preparedness will the public buy?
- Who will pay for required seismic strengthening measures?
- Should costs be calculated for one major event or on an annualized basis?

Legal Objectives

- Who is liable for the failure of municipal services?

- What liability is attached to post-earthquake repair efforts and emergency operating decisions?

CURRENT STATUS

The current status of water and sewage lifeline systems with respect to emergency response varies widely and depends on the size of the system and the perceived level of risk.

Operations and Maintenance

In general, field repair crews are well-trained in emergency pipeline repairs because their day-to-day work is commonly of an emergency nature. This is true to a lesser extent for above ground mechanical facilities. The major difference between earthquake conditions and normal operations, according to emergency management specialists at several large California water and sewer districts, is the quantity of component failures rather than the quality of failures. Because of this, optimal emergency operations depend heavily on adequate communications and coordination of effort rather than on training of field crews.

There exists a wide range of earthquake coordination and readiness in the water supply and sewage collection systems throughout the United States. In California, for example, the week containing April 18 (the anniversary of the 1906 event) is designated as a statewide earthquake awareness week. Some utilities use this opportunity to stage simulated emergencies and to test emergency communications in coordination with city, county, and state Emergency Operations Centers (EOCs).

Many large systems in seismically active zones have an emergency response plan. It must be recognized that a plan is most useful when it is practiced enough that use of the manual is unnecessary; once an emergency occurs, there is generally little time to study the manual.

Many smaller systems and those in seismic Zone 3 and 2 give less emphasis to earthquake planning than large systems and those in Zone 4. While the potential damage for the former categories of utilities is lower than for the latter, the impact of a large earthquake could nevertheless be significant because of the lack of preparation.

Maintenance procedures vary widely. For the San Francisco Auxiliary Water Supply System (AWSS), for example, two pump stations are maintained in a state of emergency readiness. At each station, one of four 750-horsepower pumps is tested weekly, and an operator is present at Pump Station No. 2 on a 24-hour basis specifically for earthquake readiness. The housings for the pumps have been strengthened with steel members. Critical valves are opened or closed periodically to ensure their operability. Deeply graphitized (corroded) cast iron water mains are repaired as funds are made available.

At the Los Angeles Department of Water and Power, backup internal combustion engine-driven pumps can be found at most pump stations, and portable generators also can be brought in to run pumps whose electrical supply has been cut off. In addition, arrangements are in place with the Fire Department to pump water with pumper trucks from hydrants at lower zones to those at higher zones if necessary. On the other hand, some other large California water utilities have no backup power for water or sewage pumps.

Several water supply systems have future plans to implement interactive computer simulation models of their system to aid in decision making. Trautmann and co-workers (1986) developed a hydraulic model of the San Francisco Auxiliary Water Supply System that predicts flows and pressures throughout the system as a function of its components and their state, including the operation of pumps, the state of valves, the operation of fire hydrants, and the presence of broken pipes. The model, which has been verified with field hydrant flow tests, can be used to evaluate the effects of damage on the ability to provide water supply at any point. The model was developed as a pilot study to demonstrate the possibilities avail able for water supply systems, and the pipe network can be customized for any system.

Models have been developed for water transmission in other areas, further demonstrating the capabilities now available; several examples include studies of water supply in Los Angeles (Shinozuka and Tan, 1981), the East San Francisco Bay area (Eguchi, et. al., 1983), the city of Kawasaki (Katayama, 1985), and water and gas supply in Utah (Taylor and McDonough, 1986).

Models of the type described above serve several useful functions. During an emergency, information can be input with respect to pipe breaks; the status of pumps, valves, and reservoirs; and domestic and fire flow demands. Various alternative actions can be tested immediately to optimize the deployment of repair crews and the operation of valves and pumps to provide the best system response. Such models could be enhanced with the inclusion of an expert system module to provide the best solution for a given set of circumstances entered by the user, based on a specified set of operating rules.

It should be recognized, however, that such models can be effective during emergency operations only if they have adequate support. Computers must have emergency power sources, and radio-dispatched crews must provide accurate damage reports. Personnel must be familiar with the computer system so that they can concentrate on the data and results rather than on operation of the software.

Retrofitting and Upgrading

Retrofitting and/or upgrading of most buried facilities is extremely expensive. Some lifeline systems are barely able to keep up with routine maintenance and increased demand caused by urban growth. Historically, it has been difficult to secure adequate funding to upgrade major portions of water distribution or sewage collection systems for earthquake preparedness. Capital funds for new construction commonly have been easier to obtain than funds for upgrading for seismic safety alone.

New Construction

Research on the design of new facilities during the past decade has greatly increased understanding of the principles of design for seismic hazards, but the transfer of technology has not been as extensive as would be desirable. Research results commonly are found in conference proceedings or research reports in a form that may not be directly usable by the practicing municipal or consulting water/sewage engineer. There is no established federal agency to contact specifically for assistance or expert referral on earthquake lifeline engineering problems on a routine basis.

Many cases can be cited where research has improved the design of new components; in most cases, however, published lifeline earthquake research has focused heavily on buried pipelines. For example, a detailed theoretical study of the slip joints used in steel water transmission pipelines showed that a relatively minor change in the manufactured shape of the joint could increase its seismic stress capacity by as much as a factor of two (Tawfik and O'Rourke, 1984). Experimental studies by Audibert and Nyman (1977), Trautmann and O'Rourke (1985), and Trautmann, O'Rourke and Kulhawy (1985) have led to a better understanding of the soil forces imposed on pipes when subjected to differential ground movements while Kennedy, Chow, and Williamson (1978) developed a procedure for evaluating the strains in continuous steel pipelines caused by abrupt fault movements. Applied risk analysis has been addressed by a number of authors; see, for example, Eguchi, Taylor, Legg, and Wiggins (1983); Mohammadi and Ang (1980); Shinozuka and Tan (1981); Katayama (1985); and Scawthorn, Yamada, and Iemura (1981). Many other specific examples could be cited.

Modeling Considerations

A major concern for system modeling is whether to use analytical or simulation models. One primary reason for using the analytical approach in the past was its computational speed. However, the power and storage now available in desktop microcomputers has, in many ways, made this a moot question. Bernoulli storage technology and laser disks (currently, these are read-only but likely will be read/write within a few years) make it possible to save almost any quantity of data required by or produced during the modeling process. Within a few years, desktop machines will have processing speeds exceeding current mainframe computers. These developments will permit virtually any required degree of complexity in simulating actual lifeline systems in real time, employing easy-to-use color graphics input and output. Modeling priorities should not be based on current hardware but rather on technology that will exist several years from now when actual development might take place.

ACTION PLAN

Improvement of water and sewage lifeline systems involves a number of short-term as well as long-term issues. To this end, several tasks are described below, with approximate funding levels and possible responsibility and agency sponsorship.

The work could be funded first as a pilot study on a selected municipality. This approach has the benefit of providing improvements to one region while fine-tuning the procedure at a relatively low cost. Once the pilot project is completed and evaluated, the concepts could be formalized and applied by other municipalities. Duplication of errors would be minimized in this way.

The time and cost estimates that follow the task descriptions should be considered only as a starting point. Additional scoping studies should be done to quantify more accurately the cost and time required to accomplish the work.

Task 1
Development of an Integrated Emergency Operation Plan

The goal of this task is to develop a flexible model emergency operating plan that can be customized for a municipality of any size in a seismically active region. The plan would make use of existing emergency plans but would include several components not currently included in such plans. A useful starting place for this task is the AWWA manual, *Emergency Planning for Water Utility Management* (1984).

Task 1a, Seminar on Emergency Response Measures

Before developing an emergency operating plan, a seminar should be held to compile ideas from a large number of municipalities who now have response plans. The purpose of this seminar would be to combine the experience of both large and small utilities and emerge with a comprehensive set of ideas covering all conceivable aspects of emergency operations. This seminar should be international in scope, as much of the experience in earthquake damage to water and sewage lifeline systems has occurred outside the United States.

Task 1b, Inventory of Components

Before any work can be accomplished on an existing system, there must be a thorough inventory of all components, their locations, and their condition. This work will involve local system engineers and planners working under the guidance of research personnel. A graphics-based mapping and relational data base approach would be useful.

Task 1c, Development of Modeling Criteria

Prior to modeling a lifeline system, which is required for any meaningful comparison of alternative improvement strategies, it is necessary to establish a practical set of objectives for the performance of the system and the constraints under which it will operate. These items include:

- Practical modeling requirements, including such issues as minimum flow requirements, probable locations of fire outbreak, etc. ISO fire ratings form a useful starting point for this task. Once a list of objectives is compiled, values must be assigned for relevant parameters in conjunction with utility engineers and managers. There must be good communication between both groups, and a practical goal must be kept in mind at all times.

- Political modeling constraints. It is not anticipated that engineers will make the value judgments necessary; however, a sensitivity approach may be warranted once the relevant parameters are established to refine their influence. Such parameters would include, for example, the weight given to health and safety vs. dollar costs; the decision to design for one major event vs. an annualized cost basis over all events, etc.

- Legal modeling framework, including any legal factors that may influence the implementation of any recommendations resulting from use of a systems model. Such factors might include, for example, evaluation of the liability associated with emergency repair efforts and emergency operating decisions (including both human judgments as well as software- generated model solutions or expert-system results).

Once these issues are resolved, it will be necessary to work within the constraints they might impose so that the model results can have the widest possible usage.

Task 1d, Development of System Hydraulic Model

A system model should be developed for a complete municipal water and sewage system, with interactive graphical input of model components and output of system performance.

Task 1e, Technology Transfer and Training of Utility Personnel

This task includes transferring the modeling hardware and software to the municipality and training local engineers and planners in its use.

Both short courses and simulated emergency drills would be used as an integral part of the training.

Task 1f, Develop Comprehensive Emergency Operations Plan

The purpose of this task is to combine the information gained in Task 1a-e to create an integrated response plan, including routine maintenance and preparedness measures, procedures and organizational structures to follow during and following an earthquake, and priorities for repair and restoration of service. Use of the system model would be included as a decision-making tool. Applicability to both small and large systems should be a goal.

Responsibility: University/private consulting firm in conjunction with pilot municipality.

Likely funding source for Task 1: Federal Emergency Management Agency, National Science Foundation

Cost: $750,000 over three years in addition to some cost sharing by pilot utility.

Task 2
Improvement of Weak System Components

Priorities should be established for the repair/upgrading/replacement of weak components identified during the inventory in Task 1b. Several steps will be required.

Task 2a, Evaluate Seismic Hazards

The hazards identified earlier (ground shaking, faulting, ground failure, etc.) should be quantified as they relate to component performance.

Task 2b, Identify Critical Components

Using the system model and the performance criteria established in Task 1, determine weak components of critical importance and establish a list of priorities for those in need of repair, upgrading, or replacement.

Task 2c, Identify Additional System Attributes and Components Necessary for Adequate Emergency Operation

Determine if additional components or increased redundancy could significantly improve operations, and make recommendations for upgrading activities.

Responsibility: University/private consulting firm in co-operation with pilot municipality.

Likely funding source for Task 2: National Science Foundation.

Cost: $500,000 in addition to some cost sharing by the pilot municipality.

Task 3
Establishment of Guidelines for Construction of New Facilities

This represents a long-term improvement goal to ensure that all future retrofitting and new construction activities are done in accordance with adequate seismic design principles.

Task 3a, Development of Design Guidelines

A comprehensive, practical, and user-oriented set of guidelines should be developed to help the practicing engineer or planner make routine and nonroutine cost/benefit decisions with respect to seismic resistance of components. In some places, this could take the form of an index to established codes or standards. In nonroutine cases, it might include results of relevant technical research found in journals and conference proceedings. A useful starting place is the pair of guidelines published by the ASCE in 1983 and 1984.

Task 3b, Development of Short Course for Training Municipal Design Engineers in Principles of Seismic Design

A short course should be developed specifically along the lines of the guidelines established in Task 3a. The course could be made available at low cost to all interested parties through partial funding by relevant federal agencies.

Task 3c, Establishment of Advisory Agency

An advisory association should be established along the lines of other governmental Public Inquiries Offices, such as those run by the U.S. Geological Survey (USGS), Nuclear Regulatory Commission (NRC), National Bureau of Standards (NBS), etc. The office would be federally funded and would support a knowledgeable executive director, several staff engineers, and a secretary. The office would serve as a national information center for emergency planning and lifeline upgrading activities and would include front-line consulting services. Additional referrals to knowledgeable experts would be available for complex problems. Other lifeline systems could be included, such as transportation, communications, etc.

Responsibility: Joint venture comprising American Society of Civil Engineers, American Society of Mechanical Engineers, American Water Works Association, Earthquake Engineering Research Institute, American Public Works Association, and Water Pollution Control Federation; coordinated by university/private consulting firm.

Likely funding source for Task 3: National Science Foundation and Federal Emergency Management Agency with cost sharing by associated groups

Cost: $3 million (with most going toward Task 3c).

PRIORITIES FOR RECOMMENDED ACTIONS

Task 1, which contains a number of distinct, though related, subtasks, should be considered a highest priority. This task, which emphasizes "using most effectively what is already available," is probably the most practical and cost-effective means of improving the earthquake performance of water and sewage lifeline systems.

Task 2, which relates to strengthening of weak components, also should be given high priority.

Task 3, which relates to improved design procedures for new construction, should be given intermediate priority for the purpose of improving the earthquake performance of current systems.

FURTHER RESEARCH

Although many of the tasks outlined above can be accomplished initially on the basis of existing knowledge, a number of uncertainties still exist that can be addressed only through sustained research efforts. Some of the most important areas include the following:

1. Procedure for making economic tradeoffs associated with repair, upgrading, and replacement schemes for weak system components. (University funded by the National Science Foundation, $300,000 over three years.)

2. Development of stronger system components, including joints and service connections. (Manufacturers working with NSF-funded researchers, $300,000 over two years.)

3. Application of existing expert system techniques to system hydraulic models to permit fast solution of emergency system management problems. (University funded by the National Science Foundation, $500,000 over three years.)

REFERENCES

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering. 1983. *Advisory Notes on Lifeline Earthquake Engineering*. New York: ASCE.

American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, Committee on Gas and Liquid Fuel Lifelines. 1984. *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*. New York: ASCE.

Audibert, J. M. E., and K. J. Nyman. 1976. "Soil Restraint Against Horizontal Motion of Pipes." *Journal of the Geotechnical Engineering Division ASCE* 102(GT11):1131-1146.

American Water Works Association. 1984. *Emergency Planning for Water Utility Management*, Manual M19, 2nd Ed. Denver, Colorado: AWWA.

Ballantyne, D. 1987. "New Treatment Facilities and Pump Stations." In *Abatement of Seismic Hazards to Lifelines*, Vol. 1. Washington, D.C.: Building Seismic Safety Council.

Eguchi, R. T., C. E. Taylor, M. R. Legg, and J. H. Wiggins. 1983. "Earthquake Performance of Water Supply Systems." In *Earthquake Behavior and Safety of Oil and Gas Storage Facilities, Buried Pipelines and Equipment*. New York: American Society of Mechanical Engineers.

Katayama, T. 1985. "Serviceability Analysis of Water System After Earthquake--A Practical Approach." In *Proceedings of the Tri-lateral Seminar-Workshop on Lifeline Earthquake Engineering*. Taipei: National Taiwan University.

Kennedy, R. P., A. W. Chow, and R. A. Williamson. 1977. "Fault Movement Effects on Buried Oil Pipeline." *Journal of the Transportation Engineering Division ASCE* 103(TE5):617-633.

Lund, L. 1987. "Water Storage Facilities." In *Abatement of Seismic Hazards to Lifelines, Vol. 1*. Washington, D.C.: Building Seismic Safety Council.

Mohammadi, J. and A. H.-S. 1980. *A Method for the Analysis of Seismic Reliability on Lifeline Systems*, Structural Research Series No. 474. Urbana: University of Illinois.

O'Rourke, T. D., M. D. Grigoriu, and M. Khater. 1985. "Seismic Response of Buried Pipelines." In *Pressure Vessels and Piping Technology--1985, A Decade of Progress*. New York: American Society of Mechanical Engineers.

Scawthorn, C., Y. Yamada, and H. Iemura, H. 1981. "Urban Seismic Risk: Analysis and Mitigation." In *Proceedings of the Review Meeting of U.S.-Japan Cooperative Research on Seismic Risk Analysis and its Application to Reliability-Based Design of Lifeline Systems*. Washington, D.C.: National Science Foundation and Japan Society for the Promotion of Science.

Shinozuka, M. and R. Y. Tan. 1981. "Estimation and Optimization of the Serviceability of Underground Water Transmission Network Systems under Seismic Risk." In *Proceedings of the Review Meeting of U.S.-Japan Cooperative Research on Seismic Risk Analysis and its Application to Reliability-Based Design of Lifeline Systems*. Washington, D.C.: National Science Foundation and Japan Society for the Promotion of Science.

Soule, F. 1907. *The San Francisco Earthquake and Fire of April 18, 1906*, U.S. Geological Survey Bulletin 324. Washington, D.C.: U.S. Geological Survey.

Tawfik, M. S., and T. D. O'Rourke. 1984. "Welded Slip Joint Response to Earthquake Axial Loads." In *Proceedings, Pressure Vessel and Piping Exhibition and Conference*.

Taylor, C. E., and P. W. McDonough. 1986. "Earthquake Risks to Utah Water and Gas Systems." *Lifeline Seismic Risk Analysis--Case Studies*. New York: American Society of Civil Engineers.

Trautmann, C. H., and F. H. Kulhawy. 1983. "Data Sources for Engineering Geological Studies." *Bulletin of the Association of Engineering Geologists* 20(4):429-454.

Trautmann, C. H., T. D. O'Rourke, and F. H. Kulhawy. 1985. "Uplift Response of Pipe in Sand." *Journal of Geotechnical Engineering ASCE* 111(9):1061-1076.

Trautmann, C. H., and T. D. O'Rourke. 1985. "Lateral Response of Buried Pipe in Sand." *Journal of Geotechnical Engineering ASCE* 111(9):1077-1092.

Trautmann, C. H., T. D. O'Rourke, M. D. Grigoriu, and M. M. Khater. 1986. "Systems Model for Water Supply Following Earthquakes." In *Lifeline Seismic Risk Analysis--Case Studies*. New York: American Society of Civil Engineers.