EARTHQUAKES AND BURIED PIPELINES:
MEXICO CITY 1985 AND BEYOND

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This paper is divided into three sections. In the first section, information on seismic damage to buried pipelines in Mexico City caused by the 1985 earthquake is reviewed. The repair and restoration techniques that were used are discussed as are as proposed plans to reduce system vulnerability and system restoration time for future earthquakes.

With the Mexico City experience as a backdrop, the second section presents a brief review of the present state of the art for seismic analysis and design of water distribution and sewer collection systems. Available methods for identifying and analyzing seismically vulnerable elements as well as available criteria for design are assessed.

In the final section, prioritized needs concerning water and sewer systems subject to earthquakes are presented. Specifically, the needs for improved pipeline joints, laboratory test, engineering analysis tools, and design criteria are discussed as is the need for developing and implementing emergency plans.

MEXICO CITY 1985

Background

The author visited Mexico City in October 1985, approximately one month after the Guerrero-Michoacan earthquake. The purpose of this consulting visit was to review damage to the water distribution and sewer collection systems in the city and to make recommendations to the Pan American Health Organization (PAHO) and the Mexican Secretaria de Agricultura y Recuros Hidraulicos (SARH). The recommendations centered around immediate repair and restoration of the existing systems, improvements to the existing systems, and planning for future earthquakes. This section summarizes the information gathered during this October 1985 visit. Since the water and sewer systems in Mexico City are similar in many respects to those in the United States (similar components, sizes, materials, etc.), it is felt that the Mexico City experience provides useful lessons for U.S. practice.

Physical Damage

There was little or no damage to the aqueducts and water treatment plants that serve Mexico City. There was, however, substantial damage to the buried pipelines that compose the water distribution system. The amount of damage to the sewer system is unknown at the present time. This lack of knowledge concerning sewer system damage is due to the fact that the unpressurized sewers pipelines are located below the elevation of the pressurized water pipelines. Hence, water system damage is easily noted by the presence of water on the ground surface or a drop in pressure while sewer damage is much more difficult to detect.

All of the buried pipeline damage in Mexico City appears to have been due to seismic wave propagation.* Since the causative fault for the Guerrero-Michoacan earthquake is located approximately 200 miles from Mexico City, no fault crossing damage was expected and none was observed. Similarly, since Mexico City is situated on either rock or soft clay deposits, no liquefaction damage was expected and none was observed. (Liquefaction and fault crossing damage to pipelines will be discussed in somewhat more detail in subsequent sections of this paper.)

In previous earthquakes, most seismic damage to buried pipelines has occurred at the pipeline joints. This was also the case in Mexico City during the September 1985 earthquake. Damage was observed at isolated joints in long straight portions of the segmented water distribution system as well as at junctions such as Ts and elbows where the pipeline is restrained by a massive thrust block. As is common in these situations, the damage was due to the inability of the joint detail to accommodate the imposed ground displacement (axial extension and axial compression) and rotation. In other words, damage was generally due to a lack of *flexibility* at the joints as opposed to a lack of *strength* in the pipe segments between joints.

Repair and Restoration Techniques Used

The priority order for earthquake repairs (i.e., which breaks to repair first) was based upon a combination of engineering and political judgment. That is, some leaks were left unrepaired temporarily because it was still possible to provide reduced water service to downstream portions of the system.

Locations of damage generally were indicated by the presence of water at the ground surface. It was not unusual for damage at a downstream location to become evident only after an upstream location was repaired and the line repressurized. Valves were closed to isolate the damaged portion. The ground was excavated and braced, if necessary, and the excavation was dewatered. In some instances, the closest valve to the break was found to be inoperable, which increased the length of the isolated portion and, hence, the time required to dewater the excavation.

The techniques used to repair the seismic damage were essentially the same as the repair techniques used in normal operating circumstances. Fabricated steel saddles were installed around damaged joints. For large diameter piping, the two half-cylinder saddle segments were bolted together with the axis of the bolts being parallel to the longitudinal axis of the pipeline as shown in Figure 1.

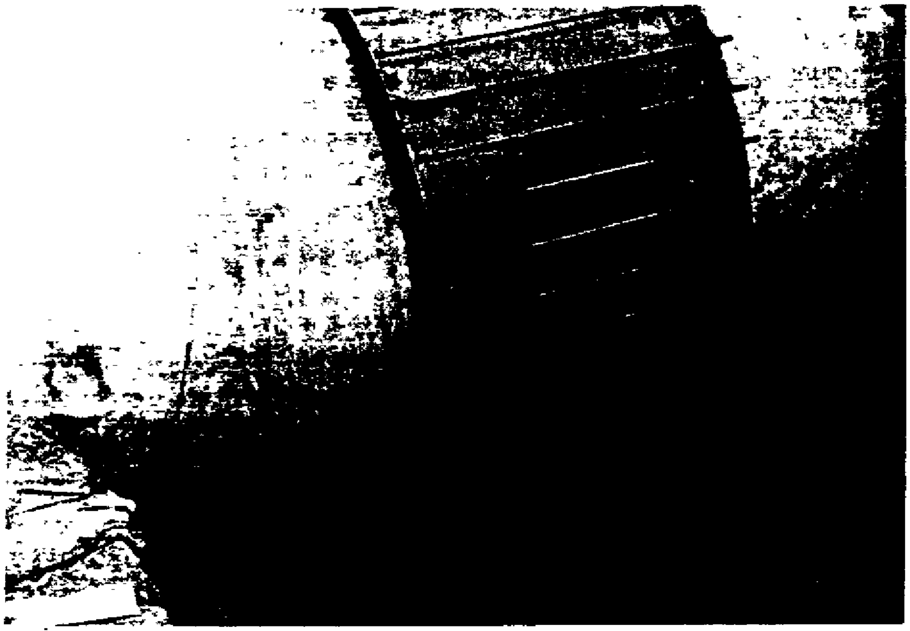

FIGURE 1 Example of repair techniques used in Mexico City.

Mexico City was fortunate in the sense that facilities capable of fabricating the repair saddles were located in the city. If the damage had occurred in more remote areas of the country or if the repair items were only available from foreign sources, the delay time associated with repair item availability would likely have been substantially longer. The author understands that few if any repair items had been stockpiled in Mexico City before the earthquake.

Repair and restoration of the water system was hindered by substantial structural damage to some of the water system buildings. The loss of records, maps, etc., as well as the time required to establish alternate headquarters resulted in some delays.

Repair and restoration of the water systems began as soon as was physically possible after the September 19 earthquake. This process continued at least through the middle of October. Water was provided to the affected or displaced populace by government water trucks.

Plans for Detailed Documentation of Damage

One of the best ways to learn about the seismic behavior of buried pipelines is to review damage to these systems caused by actual earthquakes. Hence, it is very important that written reports be prepared that describe in detail the seismic damage to water and sewer systems. This is being done by the three operating agencies that supply water to Mexico City. These reports are being collected, synthesized, and analyzed by Professor Gustavo Ayala of the National Autonomous University of Mexico (UNAM). Seismic damage to buried pipelines is usually quantified by a damage ratio--i.e, the number of breaks per unit length of pipe (usually the number of breaks per kilometer). In Professor Ayala's report, the damage ratios likely will be given as a function of:

- Geographical location
- Pipe diameter
- Type of joint
- Pipe material (cast iron, prestressed concrete, etc.)
- Orientation of pipeline axis with respect to the epicenter direction
- Soil type (soft soil, firm soil, transition zone from soft to firm, etc.)
- Pipeline configuration (damage in straight pipeline segments, damage at hard points such as thrust blocks or junction boxes, damage at interconnections or T-junctions, etc.)

Professor Ayala's report will prove useful in two regards. First, it can be used to compare the experience in Mexico City to that in other earthquakes. For example, in previous earthquakes the damage ratios for a given level of ground strain are typically higher for brittle pipe material such as cast iron than for more ductile materials such as PVC. For seismic wave propagation, ground strain, and, hence, damage ratios are usually higher in soft ground or in transition zones from soft to firm ground than in firm ground. Finally, for seismic wave propagation in a relatively uniform geological environment, damage ratios are typically higher for pipelines that are <u>parallel</u> to a radial line from the epicenter. In a relatively uniform geological environment, seismic wave propagation induces alternating extension and compression (out-of-phase motion) along radial lines, and hence, pull-out or compression failure at the joint. Pipelines perpendicular to a radial line experience uniform rigid body motion (in-phase motion) and, hence, very little strain and damage. Since much of Mexico City is located on a bowl of soft clay deposits surrounded by rock, it will be interesting to see if the Mexico City damage ratios are related to pipeline orientation with respect to epicentral lines.

Second, the damage report for the September 19, 1985, earthquake also should prove useful to officials in Mexico City as well as in other seismically active areas as they plan for future earthquakes. The report can serve as a guide for estimating the number of repair items that may be stockpiled for use after future earthquakes.

Plans for Reduction of System Vulnerability and Restoration Time for Future Earthquakes

As mentioned above, the purpose of the author's October 1985 visit to Mexico City was to review damage and make recommendations concerning repair, improvements to the existing system, and planning for future earthquakes. This section summarizes those recommendations that, in most instances, would also apply to systems located in earthquake-prone areas of the United States.

Repair Priorities

Recent publications have proposed techniques for determining the optimal order for repairs to a seismically damaged lifeline network (Hoshiya, 1981; Isoyama, 1984; Yamanda and Noda, 1984). These techniques for determining which breaks to repair first require the mathematical modeling of the network with nodes and links and also complete information about the amount and location of damage. These mathematical techniques have two major drawbacks: First, there is lack of agreement about which technique is best. Second, information about the full extent of damage usually is available only after all the repairs to the system have been made (i.e., it is not unusual for damage at a downstream joint to become evident only after an upstream joint is repaired and the line pressurized).

Because of drawbacks with the mathematical approach, it is recommended that sound engineering judgment (i.e., the technique used in Mexico City) be used to determine what damage is repaired first.

Repair Techniques

The best repair technique is one that puts the system back into proper functioning order in the shortest amount of time. In almost all cases, this involves the use of established repair techniques that have proven successful in the past during initial construction and normal operations. The use of "normal" repair procedures for seismic damage to buried pipelines has the following advantages. First, time is saved by having detail plans available for fabrication of repair items and by having work crews and supervisors familiar with the procedures. Second, one has confidence that the repair will actually work.

It is not recommended that new "earthquake resistant" repair techniques be used in the immediate post-earthquake period unless they have been thoroughly tested prior to the earthquake. Note in this regard that the use of an "earthquake resistant" repair procedure at a particular joint in a long straight run of pipe in no way guarantees that a neighboring joint will not fail during the next earthquake. The situation at bends and tees is somewhat different in that these elements are in a sense isolated as well as seismically vulnerable. Hence the use of flexible couplings (at both ends of a 90-degree bend for example) would be advisable if the work crews and supervisors are familiar with the installation procedures through past experience.

Maintenance of Valves

In order to repair damage due to future earthquakes, the damaged segments must be isolated from the rest of the water system network and the repair excavation dewatered. As mentioned above, it was discovered during the repair process that some of the values in the system did not work, thereby increasing the time required to dewater the isolated segment and, thus, increasing the time required to complete the repair.

It is recommended that all the valves in the water system be opened and closed on a regular basis, possibly once a year. Nonfunctioning valves can thus be identified and replaced so that they can be relied upon after the next earthquake as well as during normal operating conditions.

Stockpile of Repair Items

Repair items such as new pipe segments and steel saddles are needed in order to repair damage following an earthquake. It is recommended that these repair items be stockpiled so that they are immediately available after the next earthquake. They should be stored in a location such as an open yard where they themselves would not be damaged by the collapse of a building. The number, type, and size of the stockpiled repair items should be based upon the physical characteristics of the water system and the expected damage during the next earthquake. In this regard, the damage report for the Guerrero-Michoacan earthquake could serve as a guide for determining the quantity of stockpiled repair items.

Increase Seismic Resistance of System

The seismic resistance of a buried pipeline system subject to wave propagation would be increased by replacing all existing brittle materials such as cast iron or asbestos cement with ductile materials such as ductile cast iron or PVC. In addition, replacing all ordinary prestressed concrete pipe with "deep joint" prestressed concrete pipe or using mechanical coupling, which allows relatively large axial extension and axial compression at the joints, would increase the seismic resistance of the system. To do this as a restoration measure for a large system such as the one in Mexico City is financially impossible. However, it is recommended that all new construction be built with seismically resistant elements such as those described above. In addition, it is recommended that seismically resistant elements be used for normal repairs during ordinary operation of the system.

Increase Serviceability of System

The ability to supply service to as many people as possible immediately after an earthquake is a desirable characteristic of any lifeline. For an interconnected network such as a water distribution system, this serviceability is a function of the redundancy of the system as well as the capability to isolate damaged segments. It is recommended that the water distribution system in Mexico City be reviewed with an eye towards installing new interconnections between various segments or parts of the network and installing new valves that would allow damaged portions to be effectively isolated. Seismically resistant components as described above should be used for these new interconnections. In this effort, the highest priority should be assigned to geographical areas that one expects to be most heavily damaged during the next earthquake. Again Professor Ayala's damage report can be used for this determination.

Emergency Plans

In the immediate post-earthquake environment, the objective is to supply service to as many people as possible and to report the damage as quickly as possible. These activities can be done more efficiently if an emergency plan is in place before the earthquake. As outlined below, an emergency plan will not reduce the physical damage to the system but will allow the system operators to deal with the disaster in a more timely and efficient manner. Since the 1985 Guerrero-Michoacan event was the second major earthquake to impact Mexico City in the past 28 years, the need for such a plan is evident.

The emergency plan should outline the organization, location, and responsibilities of a headquarters group as well as the responsibilities of the field personnel. In order to avoid confusion, the responsibilities and chain of command for day-to-day operations could serve as a starting point for the emergency plan. For the headquarters group, a water system emergency coordinator with an alternate should be established. The headquarters location should be established with an alternate at a low risk site (i.e., seismically resistant building on firm soil or rock). Both the headquarters and alternate location should have maps of the water system, two way radios, etc. The responsibilities of the headquarters group (e.g.) as review of damage assessments from the field, issuing orders to isolate damaged portions, issuing repair orders, coordination with other local officials) should be established in the emergency plan.

Field personnel should have available a list for damage assessment in priority order for their area of responsibility (i.e., dams, water system buildings, main distribution items. etc.) as well as maps, two-way radios, etc.

It is recommended that the agencies responsible for the water distribution system in Mexico City prepare a written emergency plan. A training course on the emergency plan should be conducted for the agency personnel. Because of changes in personnel, the emergency plan should be updated on a regular basis, perhaps once every two years.

STATE OF THE ART

This section presents a brief review of the state of the art of identification and analysis of vulnerable elements of a buried water or sewer system. In addition, available criteria and methods for seismic design are presented. For a more comprehensive state-of-the-art review encompassing the special characteristics of buried pipelines, previous earthquake performance, seismic and geotechnical hazards, and buried pipeline response to wave propagation, liquefaction and surface faulting, the reader is referred to American Society of Civil Engineers (1983) and O'Rourke, Gregoriu, and Khater (1985).

Methods for Identification and Analysis of Vulnerable Elements

As alluded to previously, there are three main sources of seismic damage to buried water and sewer lifelines: liquefaction and landslides, surface fault crossing, and wave propagation. According to Youd (1978), every major pipeline break in San Francisco during the 1906 earthquake occurred in areas of lateral spreading. During the 1971 San Fernando earthquake, however, almost every pipeline that crossed a major fault break ruptured at or near the fault crossing (Youd et. al., 1978). These surface fault crossing breaks accounted for about 25 percent of all the pipeline breaks during the 1971 San Fernando earthquake. Finally, as mentioned previously, it appears that all the breaks in Mexico City after the 1985 earthquake were due to seismic wave propagation.

As far as identification of vulnerable elements is concerned, liquefaction, landslides, and surface fault crossing can be grouped together. That is, damage from these sources is relatively localized or occurs only in specific areas. For example, elements most vulnerable to liquefaction or lateral spreading (i.e., lateral movement of surface soil layers on a gentle slope due to liquefaction of a subsurface soil layer) lie close to the edges of loose saturated sand deposits. Similarly, elements vulnerable to surface fault crossing damage are located very close to main or secondary faults. The identification of elements vulnerable to seismic wave propagation damage is more difficult in the sense that damage from this source tends to occur in a fairly random fashion over a given geographical area. Recall that seismic wave propagation damage is usually quantified by the number of breaks or leaks per kilometer. Although seismic wave propagation damage tends to be heavier in soft or transition zones than in firm soil and heavier for brittle rather than to ductile pipe materials it is impossible to identify which specific pipeline joints in a given soil area are most likely to be damaged in future earthquakes. It should be mentioned that Monte Carlo techniques, such as those outlined in Appendix I of the "Water and Sewer Lifeline" section of the American Society of Civil Engineers *Advisory Notes* (1983), have been used to determine which are the most vulnerable links or nodes in a water distribution network. In this regard, a node would be a major intersection in a distribution network and a link, which is the connection between nodes, may be 5 or 10 miles long. Presently available Monte Carlo techniques could indicate which is the most vulnerable link but not which of the thousand of joints in the link is the most vulnerable.

Two things are needed in order to analyze water and sewer pipelines for earthquakes. First, the seismically imposed soil deformation must be quantified. Second, the effect of the soil deformation on the segmented pipeline must be evaluated. For liquefaction, landslides and surface faulting crossings, the segmented pipeline connects two soil masses that move with respect to one another. Although procedures exist for determining if a deposit is likely to liquefy or if a slope is likely to slide, the author is unaware of any method to estimate the expected movement, for example, due to lateral spreading. However, procedures are available that allow one to estimate the expected relative displacement for surface faulting. For example, Slemmons (1977) presents relationships between fault displacement and earthquake magnitude. There tends to be a fair amount of data scatter about these empirical relationship and the relations are typically for the maximum displacement along main faults.

For seismic wave propagation, the soil deformations of interest are axial strain (tension and compression) and, to a lesser extent, curvature. Procedures for estimating these soil deformations were originally developed by Newmark. Newmark's procedures are directly applicable to body wave (shear or pressure wave) propagation. More recently, Shinozuka and co-workers (1983) and O'Rourke and co-workers (1984) have developed procedures for Rayleigh wave propagation for a layered soil deposit over rock. A problem of estimating the expected soil strains in transition zones has received some limited attention (Dezfulian and Seed, 1969; Niva and Hirose 1984; Ohtsuki and Yamahara; 1984; Wajcik, 1979).

Once the soil deformation has been quantified, the effect of the soil deformation on the segmented water and sewer pipelines must be evaluated. Again, liquefaction, surface fault crossing, and landslides may be viewed together since the associated soil deformation is an abrupt differential movement. For differential movements that induce <u>tension</u> in a segmented pipeline, O'Rourke and Trautmann (1981) have developed the likely failure envelope for lead joints, mechanical joints, and extra long restrained couplings. The maximum tolerable differential displacement ranges from about 1 to 6 inches for lead and mechanical joints and from about 6 to 13 inches for extra long restrained couplings. The maximum tolerable displacements for differential movements that induce <u>compression</u> are expected to be less.

For seismic wave propagation, procedures for estimating relative displacement and rotation at joints exist for long straight runs of segment pipeline (American Society of Civil Engineers, 1983; O'Rourke et.

al., 1985). In general, these procedures assume similar elastic properties at each of the joints in the straight run of pipeline and the pipeline soil interface is modeled as an elastic spring. Hence, for a relatively uniform soil strain environment, all the joints in the run would experience similar seismically induced relative joint displacements. In actual pipelines, joint properties are not elastic and also vary somewhat from joint to joint. In addition, the pipeline soil interface is more accurately modeled by elastic-plastic elements with some variability from segment to segment. That is, the present models are analogous to a chain with equal strength links while the actual system is analogous to a chain with both strong and weak links. This more realistic model has not as yet been studied in detail; however, one expects that the relative joint displacements would vary from joint to joint for a relatively uniform soil strain environment with leakage or breakage occurring at the "weak links."

Procedures for evaluating seismic wave propagation effects at bends, tees, and junctions of segmented buried pipelines are not presently available although these are locations where damage often occurs.

In summary, significant progress has been made towards the identification and analysis of seismically vulnerable elements in water and sewer systems. However, as indicated above, a number of technical questions must be answered before these methods can be expected to yield useful information for design or retrofitting.

Available Criteria and Codes

The more recent model seismic codes for building structures present statically equivalent lateral design loads that are functions of the location of the structure, the importance of the structure, local soil conditions, the type of structural system, and the building's natural period. This level of sophistication and detail is not to be found in presently available seismic design criteria for buried segmented pipelines. In point of fact, the author is unaware of any U.S. code that specifically addresses the seismic design of buried segmented pipelines. The available design guidance is primarily contained in *Advisory Notes on Lifeline Earthquake Engineering*, which was published in 1983 by the American Society of Civil Engineers. Somewhat updated information is available in the state of the art review by O'Rourke and co-workers (1985). The *Advisory Notes* essentially present a review of existing information. For wave propagation effects, the well known relationship for ground strain ε

$$\varepsilon = V_{max}/C$$

is presented where V_{max} is the maximum ground (particle) velocity and C is the propagation velocity of the governing seismic wave with respect to the ground surface. The use of compressible backfill with a trench with sloping sides or placing the pipeline in a large sacrificial culvert are a few of the suggestions for surface fault crossing locations. For liquefaction and landslide hazards, the *Advisory Notes* suggest avoiding the vulnerable areas. The *Advisory Notes* do not, however, establish target design levels. For example, the return period to be used in establishing the peak ground velocity V_{max} is not specified.

NEEDS: WHAT, WHO, AND HOW MUCH

In this final section, recommendations concerning needs for new pipeline products and new engineering and planning tools are presented. Each need is given a priority ranking--I, II, or III with priority ranking I being the highest. Besides describing what is needed, this section also identifies which type of organization could do the work (the "Who") and estimates the likely cost (the "How Much"). The recommendations are summarized in Table 1.

TABLE 1 Water and Sewer Lifeline Needs

Item	Priority	Likely Organization	Estimated Cost
Improved pipeline joints	I	Manufacturer and/or manufacturer trade organization; tests by university or independent research lab	$150,000 to $300,000 per material
Analysis tools for pipeline design			
Seismic wave propagation	I	University or independent organization	$200,000 to $300,000
Ground strain at transition zones	I	University or independent organization	$150,000 to $300,000
Quantify differential soil movement	III	University or independent organization	$100,000 to $200,000
Analysis tools for redundancy	I	University or independent organization	$300,000 to $500,000
Lab tests	II	University or independent research lab	$200,000 to $400,000
Design criteria and codes	II	Existing code writing groups	$70,000 to $150,000
Emergency plans	I	Operating agencies	$100,000 to $200,000

Improved Pipeline Joints

Irrespective of the type of seismic hazard (i.e., fault crossing, wave propagation, etc.), the joints in buried segmented pipelines are the elements that suffer damage. There is a need for the development of improved pipeline joints. An improved joint should be able to accommodate, without leakage, significant rotation between two pipeline segments as well as significant axial extension and contraction between segments. This development effort should include full scale testing in both a simulated wave propagation environment as well as in a simulated fault crossing, liquefaction, etc. (i.e., abrupt differential movement) environment.

"Long sleeve" type joints are presently available for certain pipe materials but the author is unaware of any full scale tests of these "earthquake resistant" joints in simulated earthquake environments.

Pipeline manufacturers, either as individuals or through organizations such as the Ductile Iron Pipe Research Association, must be heavily involved in this effort to ensure that the improved pipeline products can be manufactured economically. University or independent research laboratories may be involved in the testing portions of the program.

The author gives this a priority ranking of I and recommends that the product development costs be borne by the manufacturers with matching funds provided for the testing portion of the program. The matching cost (i.e. non-manufacturer portion) is estimated to be about $150,000 to $300,000 per material group (prestressed concrete, ductile iron, etc.).

Analysis Tools for Pipeline Design

As mentioned previously. there are gaps in the knowledge base for seismic design of buried segmented pipelines.

Needed are engineering tools for the analysis of segmented pipelines for seismic wave propagation effects. The items that need to be addressed are the behavior of bends and junctions and the effects of the nonlinear nature as well as the variability of system parameters. These new engineering analysis tools should be benchmarked through comparisons with observed damage from actual earthquakes. This effort is given a priority ranking of I because this information is needed for the design of new systems as well as for vulnerability analyses of existing systems. The work would most likely be done by universities and/or independent research organizations at a cost of about $200,000 to $300,000.

Also needed is information on the ground strain and curvature environment at transition zones from soft soil to firm soil or rock. Most previous work has focused on amplification or deamplification at transition zones but the author is unaware of any previous work directed specifically at horizontal ground strain at these zones. This information is needed for the design of new water and sewer systems as well as for vulnerability analyses of existing systems and is given a priority rating of I. The work would most likely be done by universities and/or independent research organizations at a cost of about $150,000 to $300,000.

There is a need for methods to quantitatively predict differential soil movements due to landslide and liquefaction. Since these hazardous areas should be avoided in new construction, this information would be useful mainly in vulnerability analyses of existing systems. In addition, if liquefaction or landsliding do occur, it seems likely that they would damage existing systems. For these reasons, this need is given the lowest priority rating of III. This work would most likely be done by universities or independent research organizations at a cost of about $100,000 to $200,000.

Analysis Tools For Increasing System Redundancy

As mentioned previously, the ability to supply service to as many people as possible immediately after an earthquake is a desirable characteristic of any lifeline. For an interconnected network such as a water distribution system, this serviceability is a function of the redundancy of the system. That is, the capability to isolate damaged areas while providing service to undamaged areas is a function of the redundancy of the system.

There is a need for research on techniques to increase the redundancy of new and existing water distribution systems. Quantitative measures of system redundancy should be established as should methods for identifying which new interconnections would be most effective. The topology and hydraulic characteristics of the distribution system must be taken into consideration.

The author considers system redundancy improvements to be the most effective capital expenditures vis-a-vis water distribution system seismic resistance. Hence, this research need is given priority I. The development of these new analysis tools most likely would be done by universities and/or independent research organizations at an estimated cost of about $300,000 to $500,000.

Laboratory Tests

Force-displacement and moment-rotation information is available for some existing pipe elements. However, there is a need for more complete laboratory test data, particularly for large diameter piping. Since new buried pipeline systems in seismically active areas hopefully will be constructed with new seismically resistant elements (i.e., with "long sleeve" type joints), these laboratory tests on presently available elements would mainly be used for vulnerability analyses of existing systems. This effort is given a priority rating of II. This laboratory work could be done by universities or independent research laboratories at a cost of $250,000 to $400,000.

Design Criteria

As mentioned above, the author is unaware of any U.S. code that specifically addresses the seismic design of buried segmented pipelines. There is obviously a need for design criteria or a code. However, the author believes the analysis tools for pipeline design mentioned above, specifically work on the ground strain environment at transition zones and on the behavior of bends and junctions, should be developed before the code-writing work proceeds. For this reason, the development of design criteria is given a priority of II. In two to four years, after the analysis tools are available, this effort should have priority I.

The resulting document should be usable by both large agencies and small agencies that may not have extensive technical expertise. This effort should be done through the framework of existing code-writing groups such as the American Water Works Association. The members of the code-writing subcommittee would not be reimbursed for their time but funds should be provided to cover travel and per diem expenses. These costs are estimated to be about $70,000 to $150,000.

Emergency Plans

The Mexico City experience highlights the need for operating agencies to develop emergency plans for water systems. The author believes that these emergency plans should be developed by the operating agencies themselves. This effort should be aided by workshops organized by either state agencies such as the California Office of Emergency Services or by organizations that have a commitment to technology transfer and education such as the National Center for Earthquake Engineering Research at Buffalo, New York. The estimated cost for this activity is about $100,000 to $200,000. This estimate includes the cost for an initial workshop at which techniques for the preparation of an emergency plan are discussed and for a follow-up workshop (3 to 6 months after the initial workshop) at which the emergency plans prepared by the attendees are reviewed and critiqued. Per diem costs for the attendees also are included. However, the author believes that the cost for the attendees to actually prepare the plans in the 3 to 6 month period between workshops should be borne by the individual water systems themselves.

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