Piping damage due to sliding or toppling equipment will also be reduced by anchoring. Providing flexible connections can reduce piping damage as well. Some specific subcomponents and mitigation actions are described below.

Chlorine and chemical containers. Chlorine cylinders (150-lb [70-kg]) should be restrained at the top and bottom. Consider using sodium hypochlorite as an alternative to chlorine. One-ton (1000-kg) containers should be anchored with chain binders or nylon straps. Check with tank and container manufacturers (or the Chlorine Institute, see bibliography) for the proper method of restraint. Figure 4-2 shows temporary restraint used after the 1991 Costa Rica earthquake.

Chlorine systems can be designed and constructed with an automatic backup. A chlorine leak and control system can indicate the extent and location of a leak, actuate chlorine scrubbers, shut down equipment, and isolate affected areas.

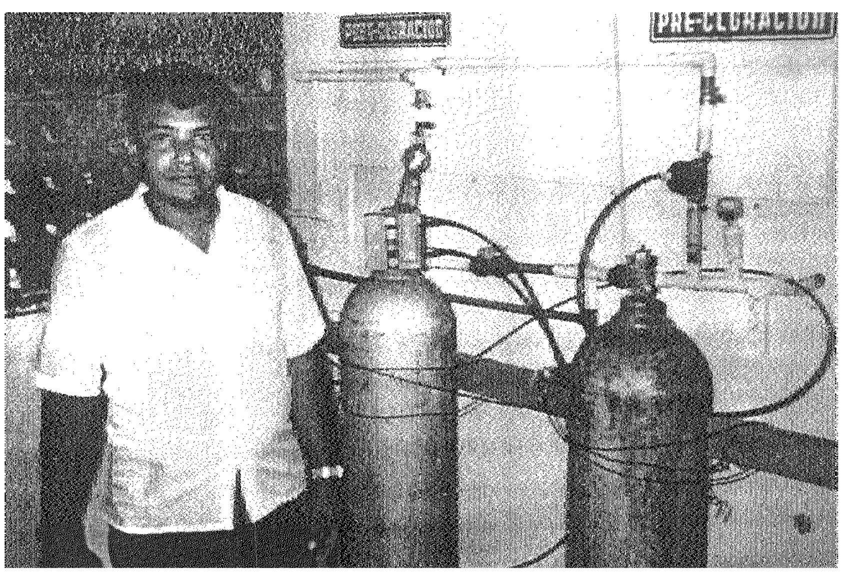
Buried tanks. Tanks subject to sinking or floating in liquefiable soils, or during flooding, can be restrained to reduce damage. Soils can also be stabilized.

Piping supported on rods from ceilings. To resist damage from swinging, support piping in three directions at right angles. Do the same for chlorine tubing.

Pipe appurtenances. Appurtenances such as valves rising vertically from pipe tend to act as pendulums that amplify ground motion. Anchor the appurtenances.

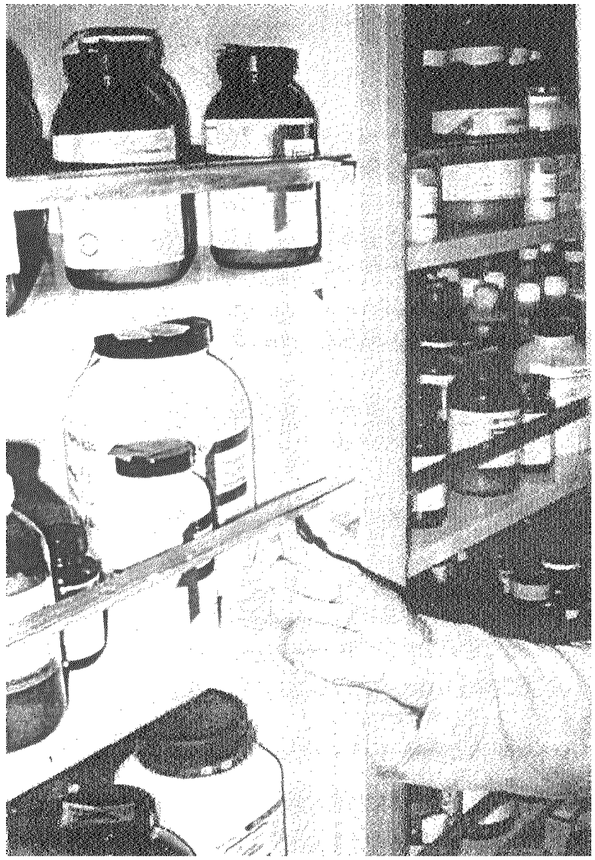
Buried piping at building edge. Provide flexible connections for differential settlement and differential lateral movement.

Laboratory equipment and chemicals. Lab equipment and chemicals stored on shelves should be provided with restraints, such as lips on the shelves or a bar installed across the face of the shelves (Figure 4-3).



Source: D.B. Ballantyne.

Figure 4-2 Chlorine cylinders replaced and temporarily restrained after toppling in earthquake, breaking connections. Costa Rica, Limon water treatment plant, 1991



Source: D.B. Ballantyne.

Figure 4-3 Brackets designed to keep lab chemicals on shelf, Rinconada water treatment plant. Photo taken after the 1989 Loma Prieta, Calif., earthquake.

Process Basins or Tanks

Mitigation of damage to process tanks is best handled in the design phase. Retrofitting tanks is difficult and often the only way to mitigate damage is by reconstruction.

The design of treatment facility tanks should include flexibility and redundancy (Hamann and Suhr 1980). For example, provide multiple connections between tanks to provide alternative configurations of tanks in series.

Specific earthquake design considerations of process tanks include the following:

- provide breakaway design or other appropriate methods for submerged elements or baffles to allow easy replacement
- use appropriate codes and design methods for concrete tanks
- perform a geotechnical investigation, stabilize the soil as necessary, and use the appropriate foundation
- design with neutral buoyancy, keep the tank full, or use piles to hold in place

Storage Tanks

As with process basins, the best time to mitigate damage from a disaster on a storage tank is during the design stage. Refer to such tank standards as ANSI/AWWA D100 and ANSI/AWWA D110. Design considerations include the following:

- use appropriate design values for earthquake, wind, and other live loads
- perform geotechnical, geologic, and seismological studies to evaluate foundation designs
- provide adequate freeboard baffling and strength against sloshing
- provide correctly positioned isolation valves
- provide pipe flexibility
- make provisions for security, such as fences, gates, lighting, alarms, and locked valves and hatches
- ensure access is available in case of flooding or other disaster hazards

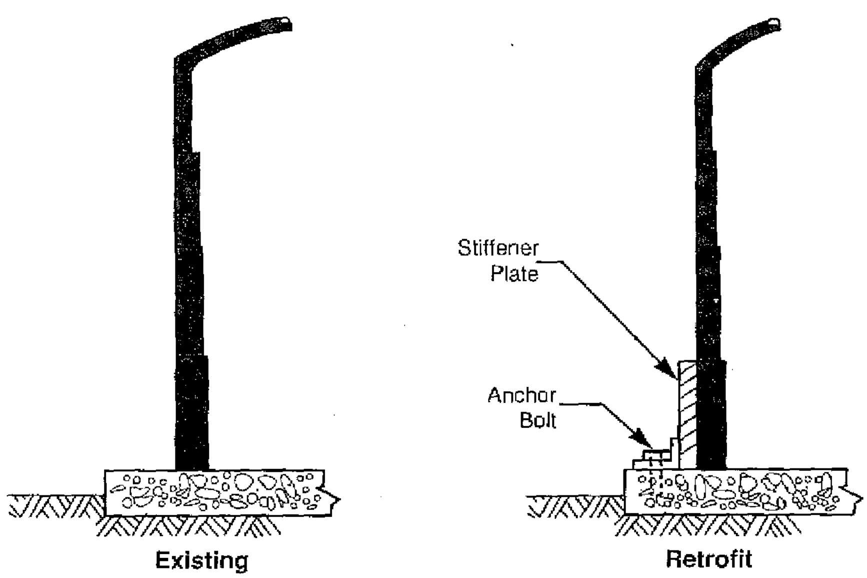
Existing tanks should be evaluated for structural soundness and performance during disasters. Specific mitigation actions for existing tanks of various types include those listed below.

Wire-wrapped concrete tanks. Check for vertical-cracking delamination and water corrosion staining on the outside of the tank. Check for installation of seismic cables.

Steel standpipes and ground storage tanks. Install or upgrade anchors or stiffeners (Figure 4-4). Upgrade the foundation if inadequate. Check the capability of walls to handle additional stress.

Horizontal tanks. Upgrade support to carry loads in three directions at right angles.

Elevated steel tanks. Upgrade with additional foundation strength, base isolation, and lateral support. Upgrade the steel structures and allow the bracing to yield before a connection failure.



Source: American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering 1983.

Figure 4-4 Mitigation option for water storage tanks

DISTRIBUTION

Mitigating disaster effects on the distribution component of a system can be difficult because of the numerous and widely distributed components Mitigating effects on pumping stations was previously discussed in the section on source water and transmission. Computers are useful in gathering information through regional networks to determine problem areas and damage. They can also be effective in monitoring and controlling emergency valves, and keeping inventories on equipment and suppliers. The case study below presents an example of how such a system works.

Pipelines, Valves, and Other Appurtenances

Methods of design and types of material can mitigate disaster effects on these essential distribution system components.

Pipeline design, construction, and upgrading. As with other system components, mitigating hazards is easiest in the design and construction phase Refer

Case Study: OP/NET Control System

On Oct. 17, 1989, the service area of California's East Bay Municipal Utilities District (EBMUD) was hit by an earthquake measuring 7 1 on the Richter scale The EBMUD system has over 300 facilities, including hydroelectric stations treatment plants, rate-control valves, pumping stations, reservoirs, and 3,700 mi (5,954 km) of pipeline network controlled by a distributed control system (OP/NET)

The OP/NET control system is set up so that each facility has a remote terminal unit (RTU), which monitors local conditions, provides local control, and transmits data to an area control center (ACC) These ACCs, in turn, provide local logic for control of all operating facilities in the area as well as a communication system to transmit all information from the ACCs to the central Oakland, Calif, control center (OCC). At the OCC, the information from each ACC is centralized and the entire system is operated 24 hours a day

Damage from the earthquake to facilities totaled $3.7 million. The earthquake resulted in about 200 main breaks, mostly 4–12 in. (102–305 mm) in diameter, with only two serious main breaks. Aqueduct damage was sustained by one 60-in. (1,524-mm) diameter line. Structural damage was sustained by the new headquarters building

Power was lost in the central control center and control shifted to the five ACCs until backup power was brought on.

The actual benefits the OP/NET provided during the Oct 17 1989 earthquake included the following

- immediate identification of problems as they occurred
- expedited assessment of priorities by knowing where problems were
- maintenance of customer service without interruption or contamination even though about 200 main breaks occurred
- documentation of the earthquake event showing how each communication line, electric power connection, hydraulic surge, reservoir level, and other monitors reacted to the earth movement at the over 300 facilities

Earthquake design principles included the following

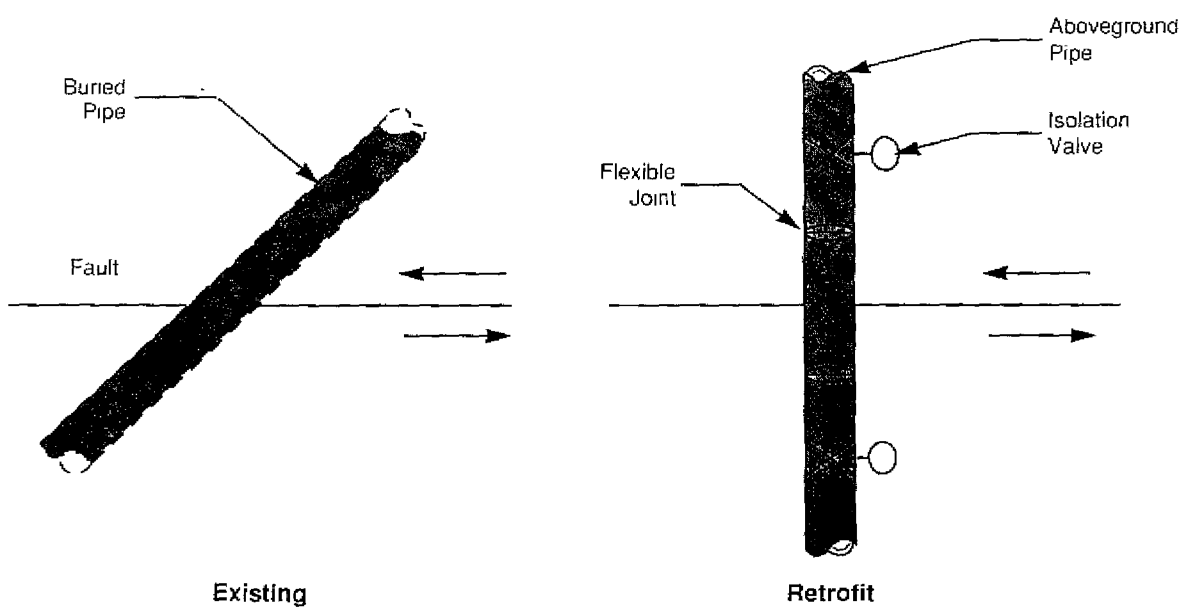
- equipment tie-down
- battery backup and emergency generators at the ACCs and the OCC: batteries at all facilities to keep the RTUs and instruments powered
- fire protection
- redundant computers to ensure over 99 9 percent uptime
- distribution control

Source Adapted from Instrumentation and Computer Integration of Water Utility Operations, *1993 Originally excerpted from Way, Jacobs, and Browne 1989, and Gilbert, Dawson, and Linville 1989* to the appropriate AWWA pipe standards for guidance. Some considerations include the following:

- use the most current pipe available (pipe materials are continually being improved)
- avoid installation in liquefiable soils and, where required, avoid areas prone to flooding and landslides
- use pipe materials suitable for the soil conditions and expected hazard
- route pipelines at right angles when crossing known faults
- use flexible expansion joints at fault crossings and where soils change to liquefiable soils
- use compressible backfill material and shallow cover when crossing known faults to permit pipe/soil movement
- stabilize soils with vibroflotation, stone columns, grouting, compaction, or other methods
- use pile supports where required
- provide operational flexibility and redundancy
- build in emergency-response capability, such as isolation valves, check valves, and automatic valves
- have a cross-connection control program

Upgrading existing pipelines should begin with those segments identified as critical in the vulnerability assessment. When upgrading pipeline segments, use the design considerations listed above for new pipelines. See Figure 4-5 for an example of a damage-mitigation procedure.

The performance of pipeline materials and joint types in earthquake hazards has been documented in many studies. The following is a summary of the results of some of those studies.



Source: American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering.

Figure 4-5 Mitigation options for pipelines at fault crossings

In general, steel, ductile-iron, and polyethylene pipe will accommodate more ground deformation than cast-iron or asbestos–cement pipe. Restrained joints provide continuity to pipelines to keep them intact in moderate ground movement. Bell-and-spigot type joints allow flexibility, but can easily be pulled apart.

High-performance pipelines, such as electric-arc-welded steel, restrained-joint segmented steel, polyethylene, or restrained-joint ductile-iron, can accommodate permanent ground deformation up to approximately 20 in. (500 mm). Average- to high-strength materials, such as restrained-joint PVC or restrained-joint concrete cylinder pipe, can handle permanent ground deformation up to approximately 4 in (100 mm). Average-strength pipelines, such as unrestrained-joint ductile-iron, PVC, concrete cylinder, reinforced concrete, cement, asbestos–cement, and segmented steel pipe, can accommodate ground deformation of less than 1.5 in. (40 mm) or up to the bell-and-spigot insertion length allowance. Average- to low-strength pipelines (tolerating less than 0.75 in. [20 mm] of ground deformation) include cast iron, vitrified clay, unreinforced concrete, and gas-welded steel. Low-strength (less than 0.4 in. [10 mm] tolerance) pipelines include cast-iron or vitrified clay with mortared or leaded joints.

Valves and other appurtenances. Provide positive flexible connections to reduce earthquake effects. Also important is an active preventive-maintenance program. Such a program should include identification of critical valves, locating them in the field, and establishing reference points for location. Valve inspection and repair should be done on a regular schedule

Repair. Quick repair of broken mains and service lines is crucial in emergencies. Maintain adequate stockpiles of such materials as repair clamps, sleeves, pipe, and valves. This is especially important for materials that take a long time to deliver. The material should be stored properly to resist hazards from disasters such as earthquakes, hurricanes, floods, tornados, and vandalism. Also, maintain and have access to tools and debris-removal equipment.

System Control

Implement reliable system monitoring and control systems. The monitoring system should gather information on pressures and flows. The control system should allow isolation of areas damaged in earthquakes.

Interagency Connections

An interagency distribution system connection is a physical connection between the water sources operated by adjacent water agencies (Boyle 1980). The typical interconnections consist of valves and a meter, and a structure that can be a simple in-ground vault or an aboveground pumphouse. If the two water systems operate at significantly different pressures, a pump or regulator will be needed at the interconnection to reduce the pressure differential. A written agreement between agencies should specify the conditions of use, necessary notifications before use, construction and maintenance responsibilities and operational procedures. Raw water transfer between agencies may also be considered.

ADMINISTRATION, TRANSPORTATION, AND COMMUNICATION

Administration facilities, equipment, and records are vital to the operation of a water system. Structures that house the administrative functions should meet applicable