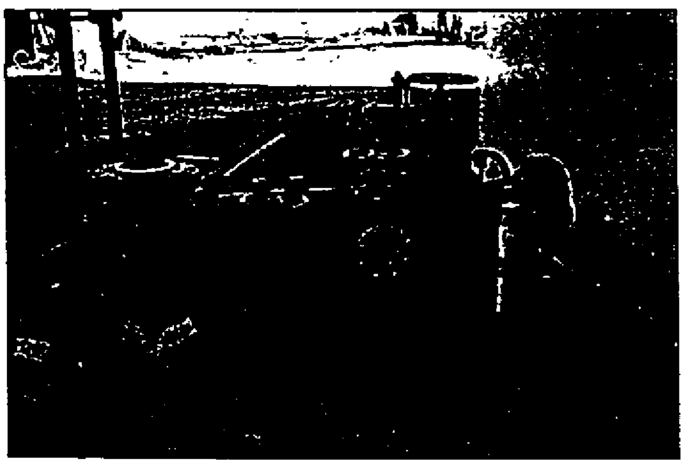


Photographs 3-88 and 3-89. Broken fitting and repaired connection on unanchored Scotts Valley tank following Loma Prieta earthquake.

If the connection is on the bottom, the setback between the tank wall and connection must be adequate. Steel tanks are flexible. When the tank wall uplifts, the tank bottom deflects. Only the bottom section nearest the wall will move. Flexibility can also be provided in the bottom connection by adding an extension sleeve to accommodate the uplift. Refer to AWWA D100-84 for more detailed information.

In poor soils, differential settlement may occur between the tank and connecting piping. Flexibility should be provided.

Photograph 3-90. Connecting pipe broke as a result of ground settlement around concrete tank in Baguio, Philippines.

Roofs and supporting columns are subject to damage from sloshing water. The sloshing water will impart lateral loading on columns. Sloshing water will impact vertical upthrust loads on tank roofs, particularly around the periphery. In addition, heavy concrete roofs are susceptible to damage if the structure is not designed to transfer lateral roof loading to the tank walls and foundation.

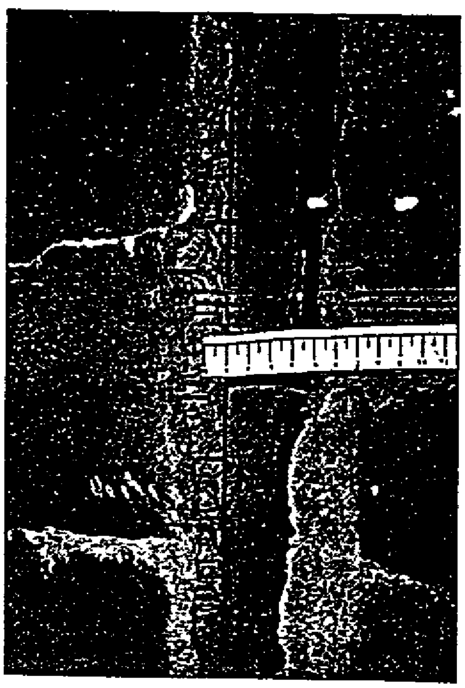
Photograph 3-91. Roof damage to steel tank from sloshing from Loma Prieta earthquake.

All tanks and reservoirs may subject to geotechnical and foundation failures. Uneven settlement is one concern, particularly when a tank is founded partially on undisturbed soil, and partially on fill. Landslides, either below or under the tank, and above or into the tank can be a concern.

Liquefaction may be a concern if the site is susceptible to liquefaction. This is unusual because tanks and reservoirs are usually located on high ground where liquefaction susceptibility is usually low. In-ground reservoirs constructed with earthen berms may be susceptible to liquefaction particularly if water is leaking from the reservoir maintaining a high groundwater table.

3.4.5.2 Wire-Wrapped/Tendon Concrete. Wire-wrapped and post-tensioned concrete tanks are vulnerable to earthquake if reinforcing has corroded, or if the roof/wall or wall/bottom joints are not designed to carry earthquake loads.

Concrete tank wire wrapping has shown tendencies to corrode in 1960s vintage tanks which has resulted in tank failure. Indications of tank deterioration are vertical cracking, spalling, or staining from tank leakage of the shot crete. These problems have been mitigated first by stopping the leaks with tank linings followed by re-wrapping the tank with wire or steel bands.

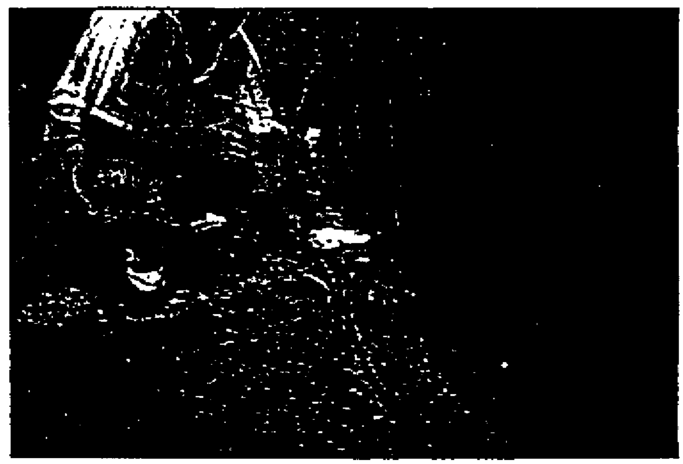


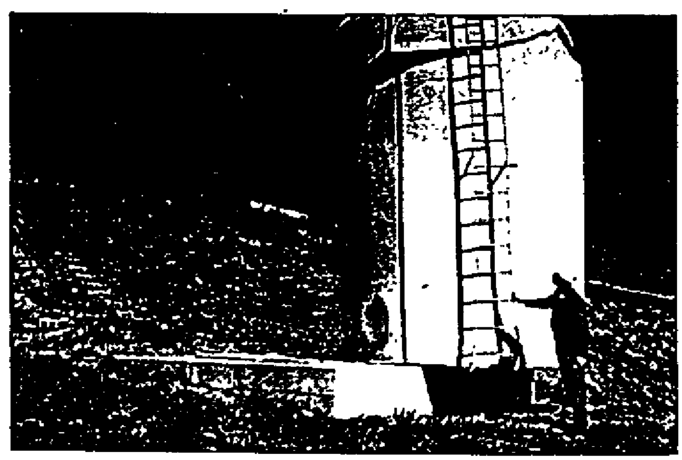
Photographs 3-92 and 3-93. Wire-wrapped 1960s vintage concrete tank failed in Loma Prieta earthquake in Parissima Hills Water District as a result of corroded wires.

Tank roof/wall and wall/bottom joints must be designed to transfer earthquake shear loads. In modern designs, earthquake cables are used between the wall and bottom. These cables allow the walls to move to accommodate strains induced from tank filling. They limit movement in an earthquake. Tanks designed prior to the 1970s did not use earthquake cables, and may fail at the wall/bottom connection in an earthquake. For partially buried tanks, the passive earth pressure should prevent shear failure. One solution is to provide a curb around the periphery to limit sliding.

3.4.5.3 Steel Ground-Level Tanks. This category of tanks is usually unanchored. When their height to diameter ratio is less than 0.5, they will typically not be structurally vulnerable, but are more likely to be vulnerable to sloshing damage to the roof.

Small unanchored tanks may slide.

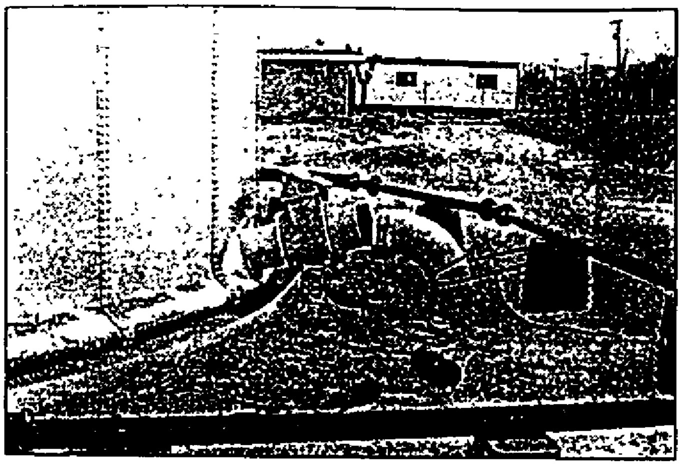




Photographs 3-94 and 3-95. Unanchored tank slid in Moin, Costa Rica; unanchored chemical tank slid in San Fernando.

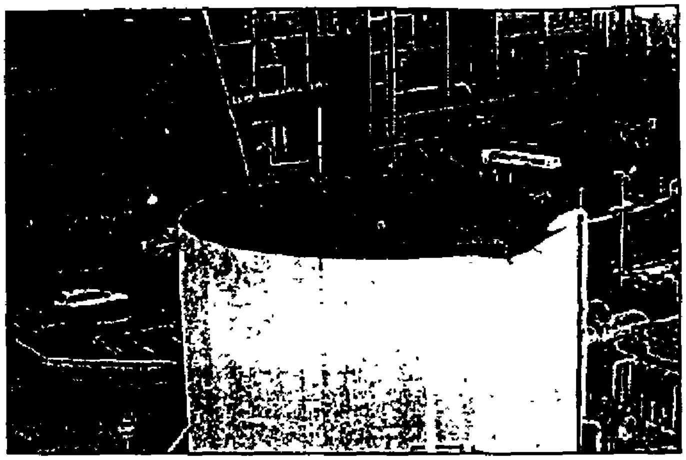
3.4.5.4 Steel Standpipes. These tanks may be anchored or unanchored. Standpipes typically have a higher height to diameter ratio than ground-level tanks described above. Standpipes may be vulnerable to elephants-foot wrinkling caused by impulsive and convective hydraulic loading

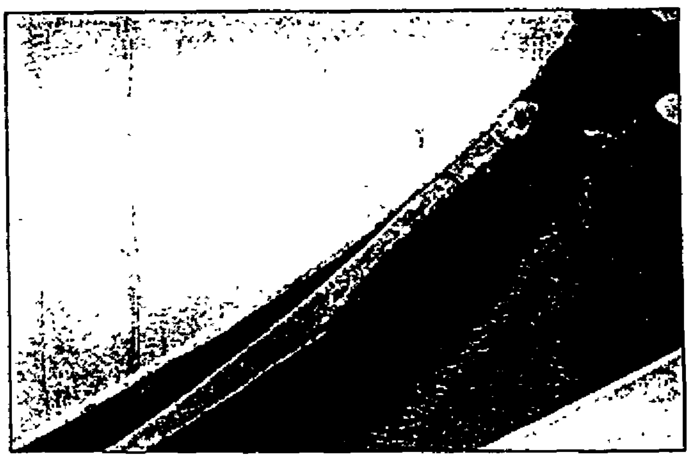
Unanchored tanks may begin to rock, and fail in compression on impact. Tanks may rupture at or near the base in extreme cases.



Photograph 3-96. Unanchored 400,000-gallon tank uplifted, breaking connecting piping, developing elephants foot wrinkling, and bursting at the discontinuity between single and double plates in the shell in Landers earthquake.

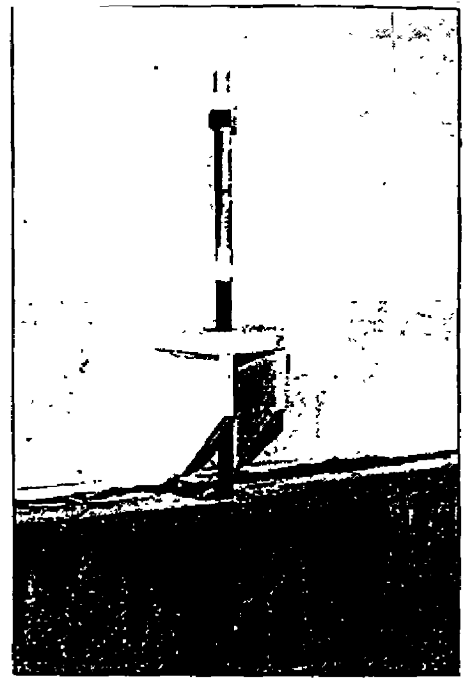
Photographs 3-97 and 3-98. Unanchored tanks developed elephants foot buckling, to the extreme of the shell folding back on itself without rupture in Moin, Costa Rica.





***Photographs 3-99 and 3-100.** Unanchored tank ruptured at the wall/bottom connection emptying its contents so quickly the top imploded.*

Adequate anchors will prevent uplift. Inadequate anchors may stretch. Stretching anchor bolts absorb energy, reducing further damage.



***Photographs 3-101 and 3-102.** Stretched anchor bolts on tanks following San Fernando and Seattle earthquakes.*

Structural solutions include adding or upgrading the anchorage/foundation system to resist uplift, or stiffening the tank bottom. Figure 3-4 shows one alternative to upgrading the anchorage/foundation system. Be sure to check the structural capacity of tank shell to transfer load and resist wrinkling. Also limit the bending movement on the shell at the anchor connection. Upgrade costs range from $75,000-$250,000 per tank for tanks ranging from 0.5 to 5 million gallons in capacity.

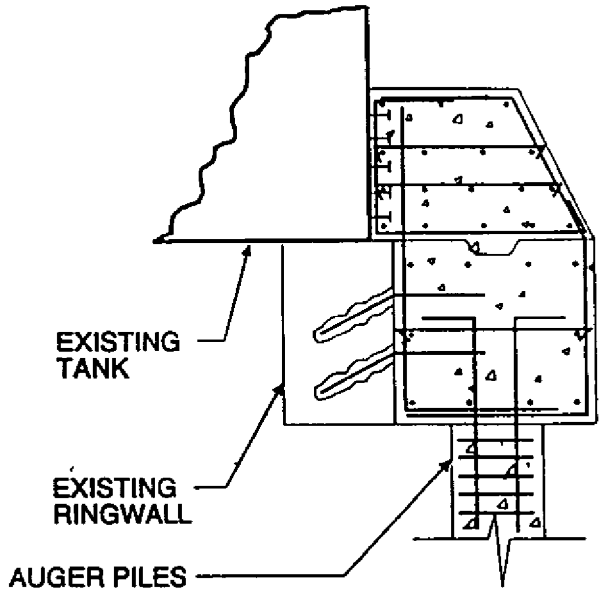
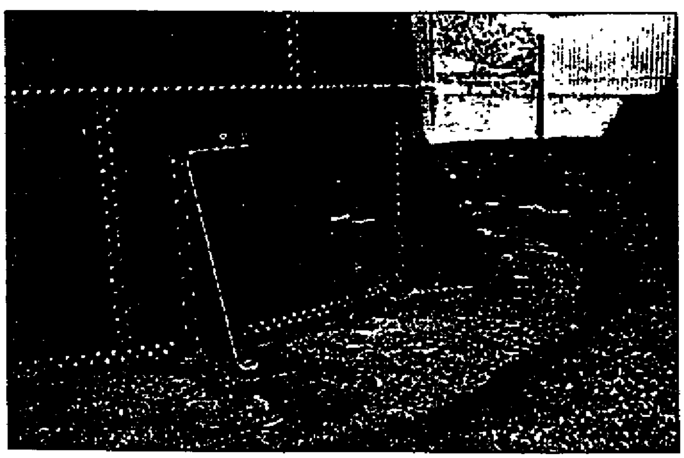


Figure 3-4. Upgrade design for steel tank using auger piles.

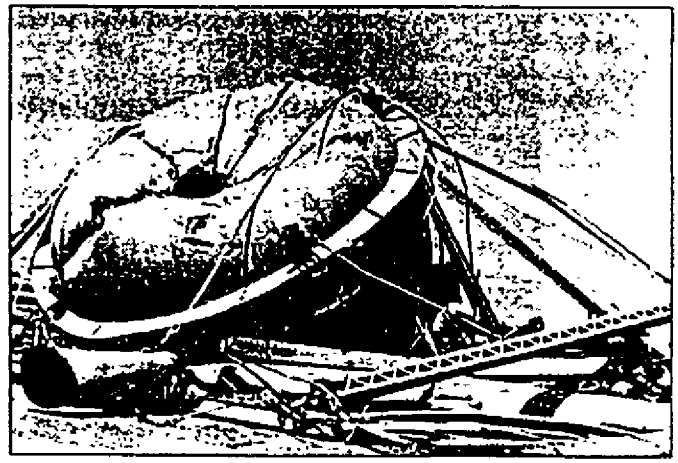


Photograph 3-103. Standpipe upgrade installed on Portland Water Bureau standpipe.

The bottom stiffening alternative makes the tank act more as a rigid body, rather than flexing as the tank responds to the earthquake. The tank can then rely on the weight of the contained water to keep it from overturning. The stiffening upgrade would be accomplished by installing a heavily reinforced concrete slab inside the bottom of the tank, and providing for load transfer from the tank wall to the slab.

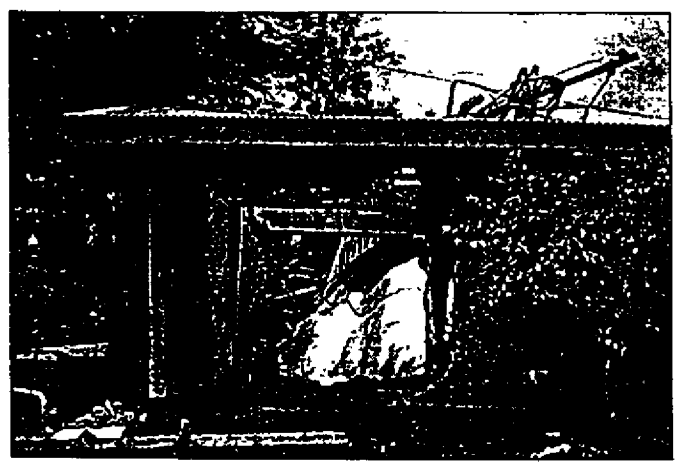
3.4.5.5 Elevated Tanks. Elevated tanks may be vulnerable as a result of inadequate foundation, column sizing, or cross bracing. These three elements make up the support structure for elevated tanks. They should be designed to be of approximate equal load capacity.

The tanks themselves are generally reliable. Usually elevated tanks that are damaged undergo either minor stretching of the braces, or catastrophic failure.



Photograph 3-104. Collapsed elevated tank.

Elevated tank failure consequences may be particularly severe because of the potential of falling on someone or something.



Photograph 3-106. Elevated tank collapsed through the police station in Umingan, Philippines.

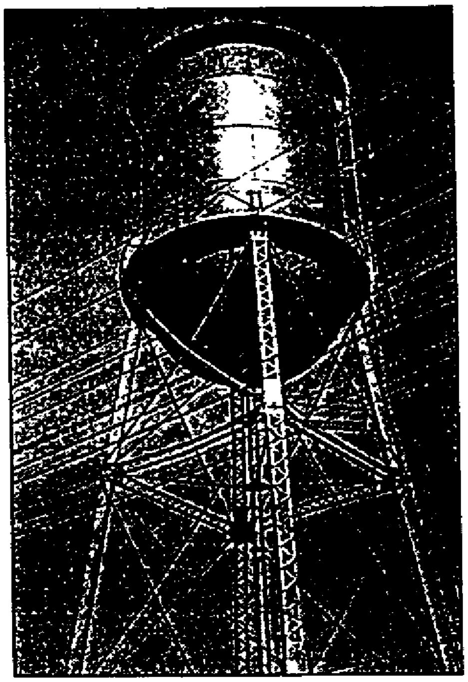
Foundations should be designed to resist overturning. To work as a system, individual column foundations should be tied together with grade beams.

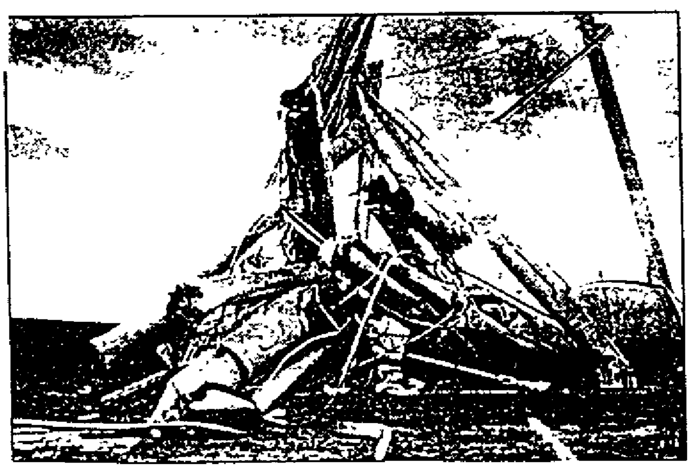
Cross brace connections should be designed to be stronger than the brace itself. This will allow the brace to stretch/yield and absorb energy, reducing overall loading on the structure

In a typical elevated tank supported with multiple cross-braced columns, they fail as follows:

- Cross-bracing member fails
- Redistributes load to other braces resulting in a torsional moment
- The domino effect takes hold and members fail progressively
- Columns buckle.

Tanks usually collapse within outline of foundation.





Photographs 3-106, 3-107, and 3-108. Tank with bent cross brace in Imperial Valley; collapsed elevated tank falling within foundation perimeter in Imperial Valley, 1979; and buckled columns of collapsed Umingan, Philippines tank.

An initial upgrade is to tighten the cross bracing.

Traditional mitigation solutions include foundation, column, and bracing upgrades. Grade beams may be added to the foundation, connecting individual column foundations. Columns may be stiffened or replaced, and bracing added. Upgrades should be undertaken to balance the foundation, column, and bracing system.

Partial upgrades may be employed, implementing the low-cost improvements such as grad beams and additional cross bracing. Care must be exercised to not overload members not upgraded.

Innovative designs for elevated tanks can include base isolation (Seattle Water), energy absorbing cross bracing, or tuned dampers (U tube in tank). The cost of engineenng for these innovative approaches may be more than for classic designs, bu the overall project cost may be reduced.

The cost of a full elevated tank upgrade can range from $100,000 to $500,000 for 0.1 million to 1.0 million-gallon tanks.

3.4.6 New Tank Design Standards

New tanks should be designed in accordance with the latest version of:

- AWWA D100, Welded Steel Tanks for Water Storage
- AWWA D110, Wire-Wound Circular Prestressed-Concrete Water Storage Tanks
- UBC
- American Concrete Institute 350, Environmental Engineering Concrete Structures
- American Petroleum Institute 650, Welded Steel Tanks for Oil Storage.

3.5 SYSTEM MONITORING AND CONTROL

The proposed strategy to overcome water loss from pipeline failure following an earthquake is to monitor earthquake ground motion and/or water system pressure or flow. Based on that information, damaged segments of the water system can be isolated to save water. Either reservoirs can be isolated from damaged piping in the distribution system or damaged areas of the transmission/distribution system can be isolated from the system segments that remain intact.

3.5.1 Reasons for Using Monitoring and Control Systems

Monitoring and control systems may be applicable because 1) water tanks have drained from pipeline breaks in recent earthquakes, and 2) vulnerable pipelines are too expensive to replace.

Pipeline failure during earthquakes, and resulting reservoir drainage, is common. Water that is lost immediately following an earthquake often cannot be replaced for days as a result of power outages making pumps inoperable or transmission system pipeline damage.

In the 1987 Whittier Narrows earthquake, one reservoir in the City of Whittier, California water system drained down approximately four feet through damaged system piping before crews could isolate the tank. The earthquake occurred during normal working hours. Had it occurred at night or during a weekend, the tank would likely have drained completely. In the 1989 Loma Prieta earthquake, the San Francisco Auxiliary Water Supply System did not provide water needed for fire protection in the Marina District because pipeline system damage caused the Jones Street Tank to drain. In that same earthquake, the reservoir serving a key pressure zone in the Santa Cruz water system that served two hospitals, drained. The system could not be refilled after damage was isolated because of a power outage. In Rio Dell, following the 1992 Cape Mendocino earthquakes, a reservoir drained because of a pipe failure at a bridge crossing. The city was without water for four days.

Replacement of water system pipeline materials vulnerable to earthquake would be prohibitively expensive as an earthquake mitigation measure. The Seattle water system has approximately 2,400 km of pipelines less than or equal to 30.5 cm in diameter and approximately 550 km of pipelines larger than 30.5 cm in diameter. Approximately 6 percent are in areas highly vulnerable to liquefaction. The large majority of the system is constructed of cast iron pipe. The estimated cost to replace the entire system with ductile iron or welded steel pipe would be over $1.5 billion. Replacing just the pipelines in particularly vulnerable areas would cost an estimated $100 million. These costs exceed the Seattle Water Department's financial capability to replace vulnerable pipelines.

A monitoring and control system alternative will mitigate the effects of some pipeline damage at a cost less than replacing vulnerable pipelines.

3.5.2 Monitoring and Control Approaches

Earthquake control of a water system can be initiated by seismic switches triggered by a threshold peak ground acceleration, excess flow through a pipeline, or reduction in system pressure. A combination of the three alternatives can also be employed.

Seismic switches shut the system down before any flooding or secondary losses, such as erosion, occur. Unfortunately, they would activate regardless of the actual system performance. It may be that pipeline damage was only moderate, and that the water supply could keep up with the system demand/system leakage. If that was the case, keeping the system in operation would be preferable to shutting it down. The peak ground acceleration triggering device threshold should be set to the point where significant pipeline damage is expected.

The advantage of triggering the isolation valve using excess flow is that it is representative of the actual system condition, that is, the valve will only close if the flow rate is high. It may also be useful to monitor for non-earthquake related pipeline failures. Care must be used in selecting the excess flow threshold where the isolation valve would close. It must allow for peak demands in addition to fire flow. It would be unsatisfactory to shut down a system that is delivering water for fire suppression, but is not damaged.

The advantage of triggering the isolation valve based on system pressure is that it may better account for overall system function rather than localized flows. The disadvantage is that it may not adequately define local system function.

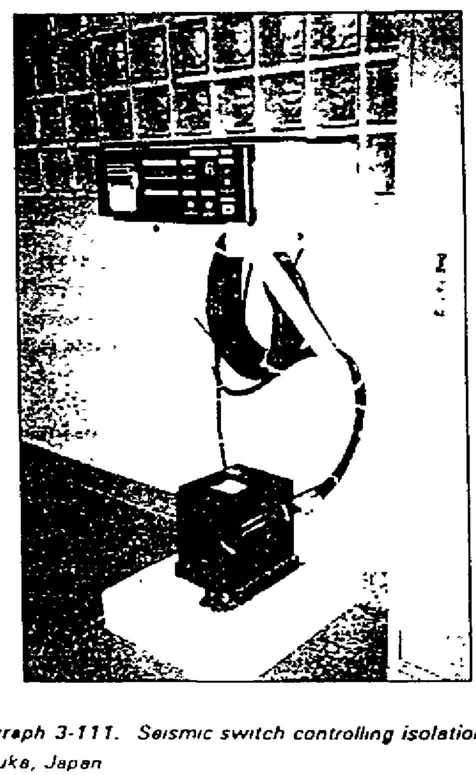
System monitoring and control decisions can be performed locally using an automated system. Local control decisions would be based on predefined threshold levels, as previously discussed. The major advantage of local monitoring and control is good reliability. The disadvantage is that the predefined threshold values may not be appropriate for all situations.

For smaller systems, it may be possible to incorporate manual valve closure for system segment isolation as part of the emergency response plan.

System status information can be transmitted to a central location using a Supervisory Control and Data Acquisition (SCADA) system, where control decisions can be made either manually or using a computer. System operators can be trained to manually isolate transmission or distribution system segments from their central location using the SCADA system. They would make their decisions based on the system status information received. System operators generally have an excellent understanding of how their systems operate and could be trained to further consider earthquake operating conditions.

Photograph 3-109. Seismically activated isolation value in Yokosuka, Japan.

Photograph 3-110. Microwater tower for SCADA system.



Photograph 3-111. Seismic switch controlling isolation valve in Yokosuka, Japan

The information could be fed directly to a computer where control decisions could be made, and transmitted back to the remote location using SCADA. An intermediate alternative would be for the operator to use the computer as a tool to assist them in making operating decisions.

The major disadvantage of central decision making is poor reliability of the SCADA system.

3.5.4 Control Valves

A range of control hardware is available, including a variety of valves and valve actuators. The primary consideration in selection of the system is reliability. The two most likely types of valves to be used for isolation would be globe valves and butterfly valves. Gate valves have been used, but are difficult to operate with stored energy sources.

Globe valves, configured as pressure-reducing or altitude valves, make use of system water pressure to actuate. They will not operate if the system has been drained. They are commonly used as altitude valves to limit the maximum water level in a reservoir or as pressure-reducing valves to feed water from a higher to a lower operating pressure zone. Their advantage is the use of system pressure for activation and the likelihood that they are already in place and being used for other purposes. Their disadvantage is that they will not operate if there is no water in the system.

Butterfly valves are used because they are actuated by rotating one-quarter turn, rather than multiple turns as required by a gate valve. This can be achieved by pneumatic or hydraulic cylinder actuators. Energy can be readily stored in the form of compressed air or nitrogen to power the actuators.

Alternatively, electric actuators are available. The system should not be dependent on continued electric power for operation. Valves that require electric actuators require emergency generators. Their capital and maintenance cost, and reliability are disadvantages.

Batteries, continually recharged by trickle chargers, are useful for operation of SCADA systems, seismic switches, and solenoids for valve piloting.

3.5.5 Isolation Configurations

Three monitoring and isolation control system configurations are described in this section.

3.5.5.1 Reservoir Isolation. Reservoirs can be isolated from damaged piping in the distribution system, as shown in Figure 3-5. An isolation valve would be installed on or near the reservoir to isolate it from the system when triggered by earthquake ground motion, excess flow, or reduced system pressure. Water would be saved in the reservoir, but the distribution system would be put out of service. Operations staff would respond by assessing the transmission and distribution systems, and isolating damaged areas. After those areas were isolated, the reservoir isolation valve would be reopened, restoring function to the undamaged portion of the system. This activity would hopefully take place quickly and in close coordination with the fire department. Potentially, water would be directed to areas where fires erupted by operations staff opening and closing appropriate valves. Saved water could also be available for tank trucks for fire fighting or drinking.

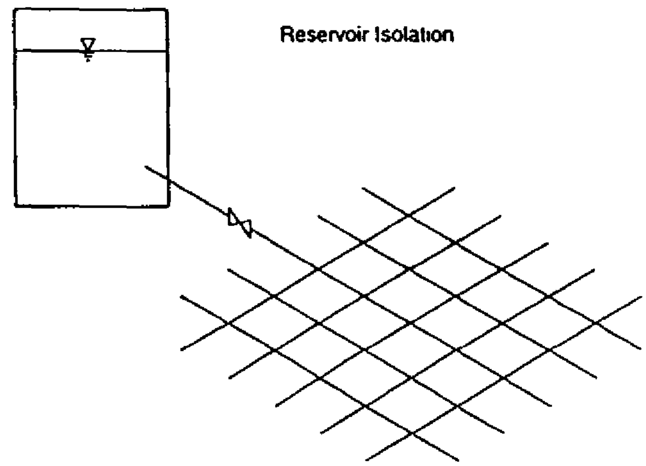


Figure 3-5. Reservoir isolation with earthquake valves.

There are several advantages to this approach. It would save water regardless of pipeline damage, assuming that the reservoir remained intact. It would be less expensive than area isolation, requiring only a single valve for each reservoir. The valve may already be in place as an altitude valve and only require additional piloting hardware.

There are several disadvantages to this approach. There would be no water pressure available to help operations staff locate leaks. The entire system would be shut down during the leak location process. This could result in liability associated with critical water service system contamination, or quick system reactivation concerns.

3.5.5.2 Isolation of Fault or River Crossings. An isolation valve could be installed on either side of a pipeline section that was highly vulnerable, such as a fault or river crossing. This configuration is shown in Figure 3-6. The same concerns for reservoir isolation are applicable for isolation of fault crossings or river crossings.

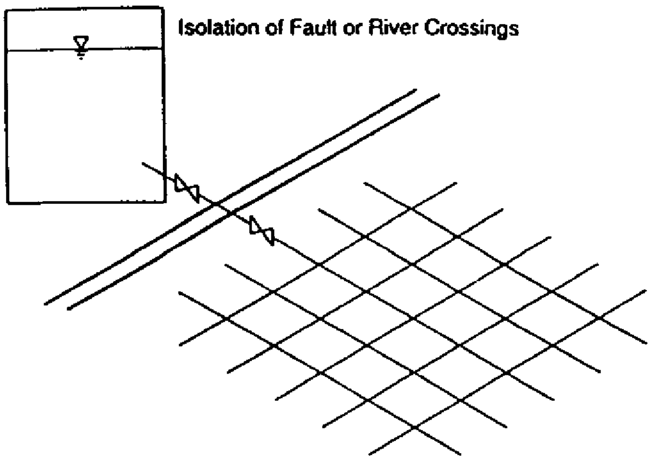


Figure 3-6. Isolation of fault or river crossing with earthquake valves.

3.5.5.3 Isolation of Vulnerable Areas. Predefined areas of vulnerable transmission/distribution system piping can be isolated from the areas of the system that will likely remain intact, such as shown in Figure 3-7. Areas that are particularly vulnerable to pipeline damage, such as those that are susceptible to liquefaction, would be isolated from the remainder of the system. The isolation valves would be triggered by earthquake ground motion, excess flow, or reduced system pressure.

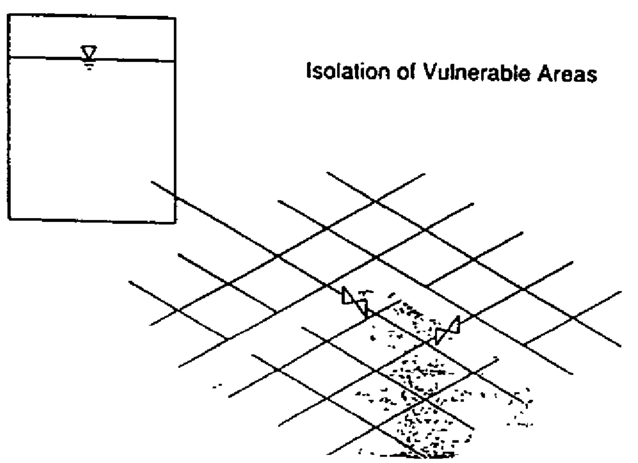


Figure 3-7. Isolation of area with earthquake valves where pipelines are vulnerable because of high liquefaction susceptibility.

The major advantage to this approach is that significant areas of the system would remain on-line following the earthquake. This could mitigate liability associated with critical water service, water system contamination, or quick system reactivation concerns.

This type of system may require installation and maintenance of new valves specifically for this purpose. It also relies on knowing where the pipelines will fail. If there was significant pipeline damage in the area not isolated, the reservoir could still drain.

3.5.6 Considerations

Water system configurations vary considerably. Whether or not a water system may lend itself to monitoring and control is dependent on the water system configuration. This section describes configurations of existing systems.

Systems such as the Seattle, Washington water system have large reservoirs feeding a few major distribution pipelines. This may lend itself to isolation of those reservoirs. Also, the Seattle system has one particular area that is much more vulnerable to liquefaction than other areas. This area could potentially be isolated.

The City of Bellevue, Washington system is fed by a single major transmission pipeline traversing its system from north to south. The hydraulic grade line of this pipeline is high enough to feed the majority of the system by gravity. The system is divided into 23 pressure zones that are fed through pressure reducing valves that cascade water down through the system. The Bellevue system may lend itself to a monitoring and control system by monitoring and isolating entire pressure zones. Control systems could be added to existing pressure-reducing valves. No new isolation valves would be required, reducing installation costs significantly.

The Memphis, Tennessee water system is supplied by a large number of small well supplies and associated at-grade reservoirs. The system is extensively intertied by a pipeline network. It would be easy to isolate a storage reservoir by shutting down a booster pump that pumps the water into the system. Unfortunately, the system is so intertied that isolating a single reservoir would not be very effective. Trying to isolate a vulnerable section of the distribution system would be difficult, requiring a large number of control valves. Also, the geotechnical situation in the Memphis area is such that there are no significant areas that have a vulnerability much higher than other areas. The Memphis system may lend itself to isolation of particularly vulnerable pipeline sections such as river crossings.

3.5.7 Concerns

Isolation of reservoirs or damaged segments of a water system following an earthquake to allow operation of undamaged areas of the systems is a viable mitigation alternative. There are concerns that system segments will inadvertently be isolated either when no earthquake has occurred, or when an earthquake has occurred but has not done much damage to the water system. This section addresses those concerns.

3.5.7.1 Liability Associated With Critical Service. Continued water supply is critical for service categories such as kidney dialysis patients, hospitals, large computer/communications installations, and fire sprinkler systems. Fire sprinkler systems may be even more critical following an earthquake. The isolation control systems discussed herein propose automatically shutting down segments of a water system. There is a concern that there may be liability associated with such systems, particularly if the shut-down occurs as a result of control system malfunction. For example, a building with fire sprinklers could burn; hospital operations could be impaired.

3.5.7.2 Contamination of Potable Supply. When a water system is shut down and drained by continued water use, there is an increased probability that the system will be contaminated by back-siphoning through cross-connections or infiltration of contaminated groundwater. The probability is increased following an earthquake if water and sewer mains are broken, which may allow passage of sewage into the water main. For this reason, water purveyors have procedures in place to keep systems in operation. If systems are intentionally shut down, operations personnel go to great lengths to minimize the chance that lines are contaminated. This is a time-consuming process.

3.5.7.3 Quick System Reactivation. Filling pipelines can be a time-consuming process. Normally, when a pipeline is emptied and being refilled, or being filled for the first time, it is done very slowly to allow air to escape and minimize water hammer, which may result in pipe damage. Following the Loma Prieta earthquake, a portion of the San Francisco AWSS drained. The fire department decided against refilling it quickly because of concerns over water hammer and further system damage. If a segment of a water system is inadvertently shut down and drained, air release and water hammer should be taken into account when refilling to minimize any damage.

3.5.7.4 Reliability. There are significant concerns regarding monitoring and control system reliability. Systems that are designed only to control post-earthquake system operation may be used only once every 25 years or longer. Operations staff are skeptical about maintenance of equipment used regularly, let alone equipment that would be used once in a lifetime. Piggybacking an earthquake control system on a system that is used and maintained regularly may mitigate this concern.

The local monitoring and control system may be preferable to a centralized system. The SCADA system is not only dependent on transmitting and receiving hardware at both ends, but on the transmission corridor connecting the two. Buried cables are subject to damage in earthquakes caused by lateral spreading and fault movement. Microwave towers for radio-based SCADA systems are subject to misalignment in earthquakes. Failure of a SCADA system in the Seattle water system resulted in an incorrect activation signal under non-earthquake conditions. Also in Seattle, disruption of a single buried cable resulted in water system disfunction.

Specific hardware concerns about valve sticking and energy supply reliability were previously addressed. The reliability of each monitoring and isolation control system should be evaluated when it is configured.

3.5.7.5 Cost. Installation of SCADA systems and isolation valves specifically for post-earthquake system control is expensive. It is better to use existing valves and modify their control strategy to accomplish the desired post-earthquake system control. One example is the Bellevue water system, where the system is served through a series of pressure-reducing valves. Seismic switches could be added to the pilot systems of selected pressure-reducing valves for minimal cost.

3.5.8 Recommendations

Liability, contamination, quick system reactivation, and reliability all are problems associated with inadvertent system shutdown. Inadvertent system shutdown can be mitigated by providing improved control reliability and/or use of dual supplies/reservoirs.

3.5.8.1 Improved Control Reliability. Control reliability can be achieved either by hardening the control system or providing redundancy/flexibility. System hardening can include selection of seismic-resistant systems and seismic-resistant design of each system component, such as:

- Radio telemetry systems rather than hard-wired systems because of the vulnerability of buried conduits to permanent ground movement
- Seismic-resistant structures housing system components
- Component equipment anchorage
- Backup power supplies for electric power-dependent systems.

Control system redundancy/flexibility can include:

- Both radio and hard-wired telemetry systems
- Combined seismic and excess-flow activated valves, requiring both to exceed their design threshold before activation
- Local valve control open/close decisions with central operations center control override
- Electric/pneumatic actuated operators with provision for manual override (truck-mounted valve operators)

- Control system with redundant components
- Trained emergency response personnel with clear system operations understanding and communications capability.

Photograph 3-112. Control panel on San Francisco Auxiliary Water Supply System isolation valve allows both remote and local control.

3.5.8.2 Use of Dual Supplies/Reservoirs. Provision of dual or redundant supplies/reservoirs for each system or system segment, such as shown in Figure 3-8, will minimize inadvertent shutdown concerns. The control strategy would be to isolate one of the supplies/reservoirs and allow the other to continue on-line. Two scenarios are described below:

1) An earthquake causing significant water system damage
2) Inadvertent isolation system activation.

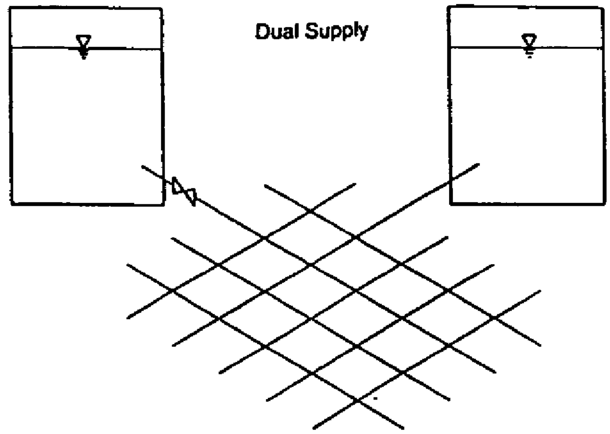


Figure 3-8. Dual supply with earthquake valve controlling one leg is preferred.

If an earthquake causes significant water system damage, the isolated supply/reservoir's water would be saved until the damaged segments were isolated. The supply/reservoir left on-line would be lost. Maintenance personnel would locate and isolate leaks, and open the reservoir isolation valve.

If the isolation system activation is inadvertent, the entire water system would remain in operation served by the on-line reservoir. The isolated reservoir would be brought back on-line when the isolation was identified by operations personnel.

There may be an instance where one supply/reservoir is inadequate to provide normal demands, but two supplies/reservoirs are needed. This needs to be considered in design of isolation systems.