Appendix E.
Mitigation Strategies for Earthquake Damage to Water Distribution Systems

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Technical Memorandum
Water Supply Forum – Regional Resiliency Project

To: Andrew Graham, HDR Project Manager

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Date: May 30, 2018

Subject: Mitigation Strategies for Earthquake Damage to Water Distribution Systems (Task 203)

1.0 Introduction

This memorandum discusses best practices that can be applied to water distribution piping systems to optimize immediate post-earthquake performance. It is limited to pipes and does not address distribution system tanks, pump stations, or other facilities. Best practices discussed herein include the ability to isolate vulnerable locations within the system that have multiple failures resulting in a high water demand, and to replace vulnerable pipe to minimize the number of failures.

The consequence of failure of pipelines can be mitigated using four general strategies:

1. Plan for and provide infrastructure to enable quick isolation of damaged pipelines (covered in this document).
2. Seismically upgrade or replace vulnerable pipe with seismic resistant pipe/joint systems (covered in this document).
3. Plan for and provide hardware for quick temporary recovery – e.g. having high-density polyethylene (HDPE) pipe and appurtenances available for temporary river, fault, or liquefaction area crossings including manifolds, to minimize restoration time (covered by other tasks in this project).
4. Plan for crews, equipment, and materials available for quick restoration – e.g. internal organization, mutual aid, on-call contractors, and pipe and repair couplings to make pipe repairs (covered by other tasks in this project).

Isolation of tanks to conserve water is widely used in areas susceptible to earthquakes. Planned isolation of areas within the distribution system that may be particularly vulnerable to earthquakes, such as river crossings and areas susceptible to liquefaction, has had limited application in the US and is discussed herein.

Identification and replacement of vulnerable pipe is an approach that has been widely adopted in seismically active areas in North America. This practice has been integrated with pipeline replacement programs driven by pipe age and potential for non-seismic failures.

2.0 Earthquake Hazards

The first step to seismic mitigation of distribution systems is to identify vulnerable locations where isolation valves or pipeline replacement may be the most effective. Historically, areas most vulnerable to pipeline damage are those with geotechnical hazards that will result in permanent ground deformation (PGD). This can include areas with high susceptibility to liquefaction, landslide, or fault zones.

Liquefaction most often occurs in alluvial deposits and is most prevalent adjacent to rivers, along lakes and other water bodies such as Puget Sound. Areas with artificial fill can also be liquefiable. See Figure 1 which shows the liquefaction susceptibility of a portion of the Seattle water system. Areas with high and moderate-to-high liquefaction susceptibility have the greatest probability of liquefaction and are of greatest concern. Lateral spread and vertical settlement associated with liquefaction, commonly reported as PGD, can occur near free faces such as along rivers, lakes or other areas with sloped topography. Pipelines and pipe bridges in liquefiable soils and buried river crossings are vulnerable. The banks of rivers with liquefiable soil can slump into the river, carrying the buried pipe with them. Having the ability to isolate river crossings may be appropriate.

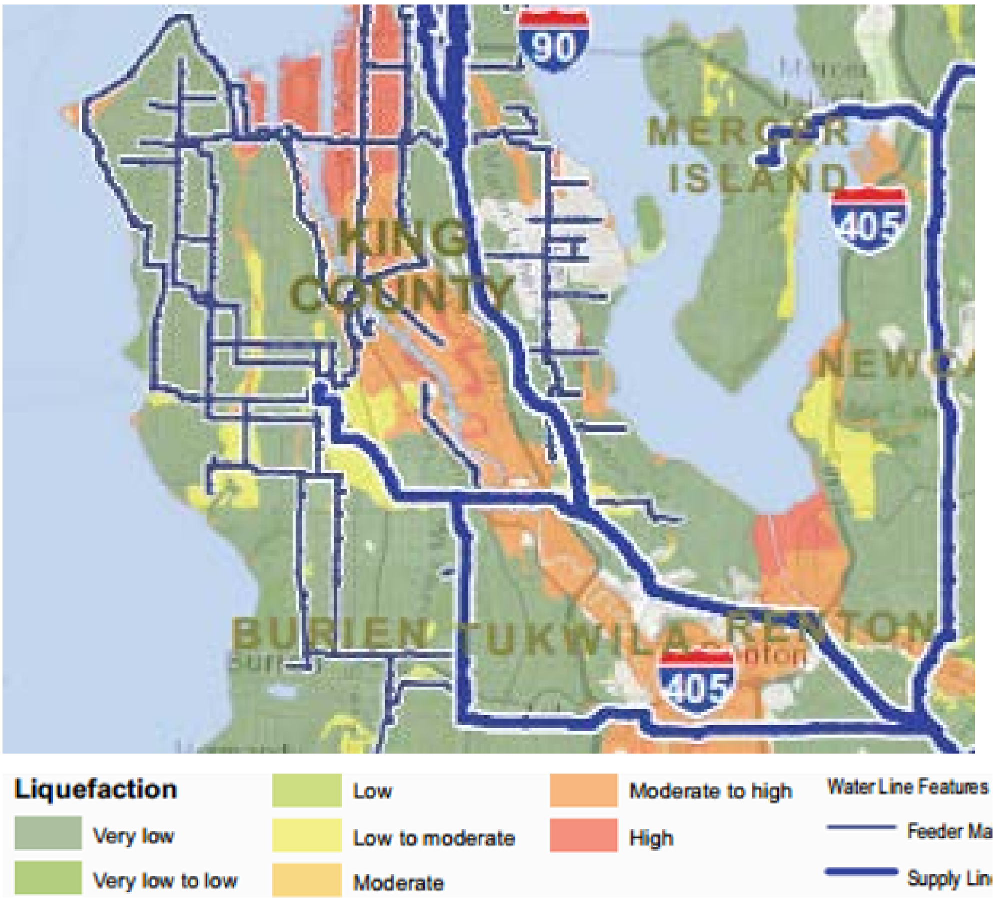

Figure 1. Example liquefaction map covering part of the Seattle water system

Liquefaction probability and PGD are dependent not only on liquefaction susceptibility but also the shaking intensity measured as peak ground acceleration (PGA), and duration of strong ground shaking. Significant liquefaction is expected to occur during long duration subduction earthquakes. Liquefaction only occurs below the groundwater table, so shallow groundwater can exacerbate liquefaction. Liquefaction susceptibility mapping in GIS format, particularly in urban areas, is available from the Washington State Department of Natural Resources (DNR), and emergency management departments. In most cases, PGD mapping is not available and will have to be developed by a geotechnical engineer on a project–by-project basis.

Landslides also result in PGDs that can range from a few inches to many feet. It is very difficult to design pipelines to withstand PGDs of many feet, so the ability to quickly isolate these lines is important. Landslide zone mapping may be available from the DNR or local emergency management departments. The technology to estimate PGDs for landslides is less developed, making them more difficult to estimate than for liquefaction.

PGD also manifests itself where earthquake crustal faulting occurs. In the Puget Sound region, crustal faults all have some component of reverse faulting (vertical movement). Crustal faults in the region include the South Whidbey Island, Seattle, and Tacoma faults. All of these faults result from compression of the North American Plate. In all of these cases, there are multiple “strands” with evidence of past movements associated with the fault, and mitigation could require addressing all of the strands. In all fault locations PGD may occur tens of feet on either side of the primary fault. It is best to consult with a geotechnical engineer to develop information about PGDs that could result from surface fault ruptures on crustal faults

3.0 Consequence of Failure

Once vulnerable areas have been identified, the consequence of failure should be taken into account and should consider:

- Consequence of loss of supply
    - Fire suppression effects
    - Outage impacts – for essential facilities, public health, potable, and commercial use
- Available water supply/storage to the affected area
- Size of vulnerable/impacted area

The impact of pipeline damage on water supply to essential services and water for fire suppression to high risk structures should be considered – so vulnerable areas that will impact these services can be isolated.

In some cases, the supply to vulnerable areas may be robust with a large capacity source or redundant sources. Isolating those areas may not be necessary to improve resiliency for essential services. In other cases, the pipeline damage in the vulnerable areas may result in significant loss of pressure, so isolation may still be necessary.

4.0 Isolation as a Mitigation Measure

Isolating tanks to keep them from draining is a practice that has been implemented for decades, with a great success in Kobe Japan following the 1995 Kobe Earthquake. Kobe had included earthquake valves on approximately 10 percent of over 200 reservoirs in the distribution system. All of these were at installations with divided tanks that could be operated separately. In the 1995 earthquake, nearly all of the earthquake valves operated as planned, conserving water. The remaining reservoirs in the system drained in approximately six hours due to over 1,000 pipe failures in the system. Figure 2 shows a schematic representation of the distribution of those reservoir service areas within the City.

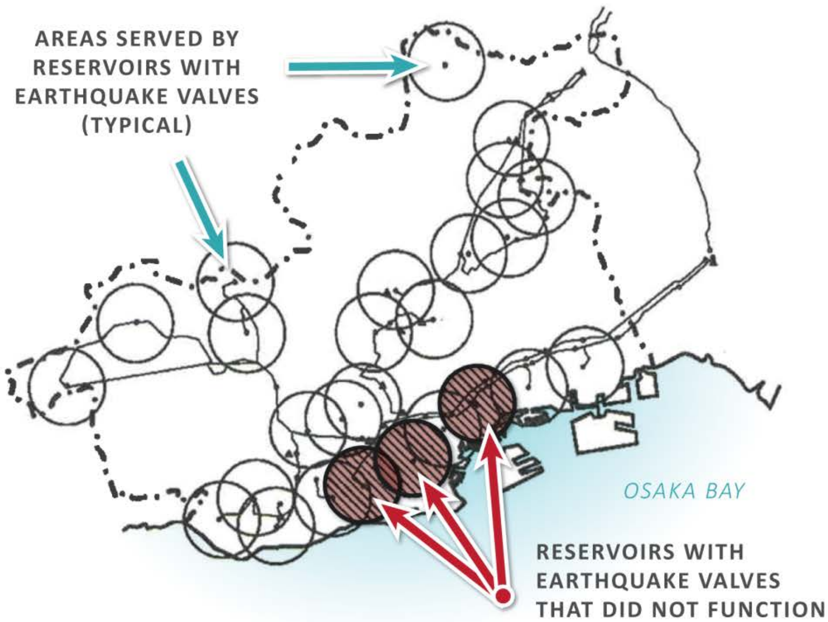

Figure 2. Schematic View of Kobe Water Service Area Showing Reservoirs with Earthquake Valves and their Respective Service Area

San Francisco's dedicated fire protection system employs isolation valves on the periphery of areas susceptible to liquefaction. These valves isolate the vulnerable areas while protecting nearby areas within the system, keeping them in operation. See the schematic in Figure 3.

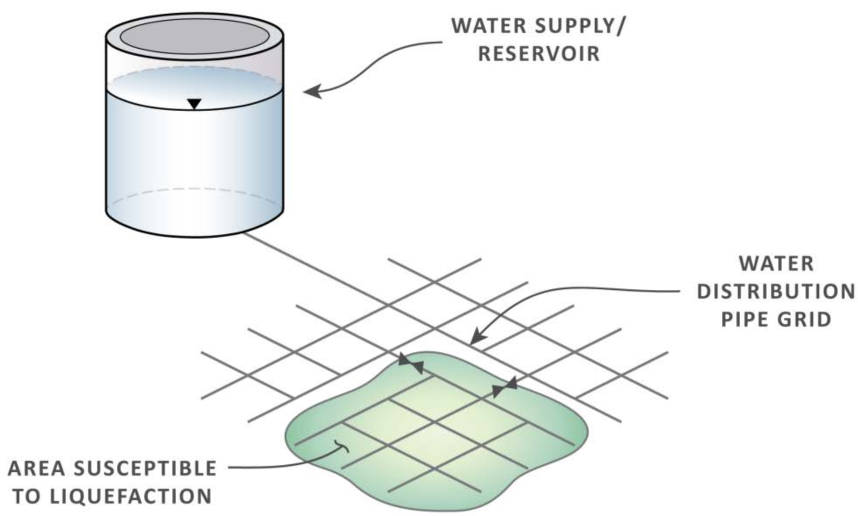

Figure 3. Schematic of system similar to San Francisco's dedicated fire protection system Earthquake Hazards

There is a range of isolation valve system strategies with varying levels of sophistication and expected performance. A list of isolation approaches and associated strategies are described below:

- Tank and reservoir isolation
- Manual isolation valve closure
- Remotely operated or automated isolation valves

Tank/Reservoir Isolation - In service areas with a large percentage of pipe in liquefiable areas, tank seismic isolation valves are often used. Isolating the tank or reservoir would save the water in the tank from draining out through damaged distribution pipelines. To use isolation valves on tanks or reservoirs, it is recommended that the service area (pressure zone) has two supplies/reservoirs, so that if one is isolated from the system, the system is still pressurized (See Figure 4). With the contents of one reservoir isolated, it gives the operations staff an opportunity to use the stored water where it is most needed – fire suppression, post-earthquake drinking, etc.

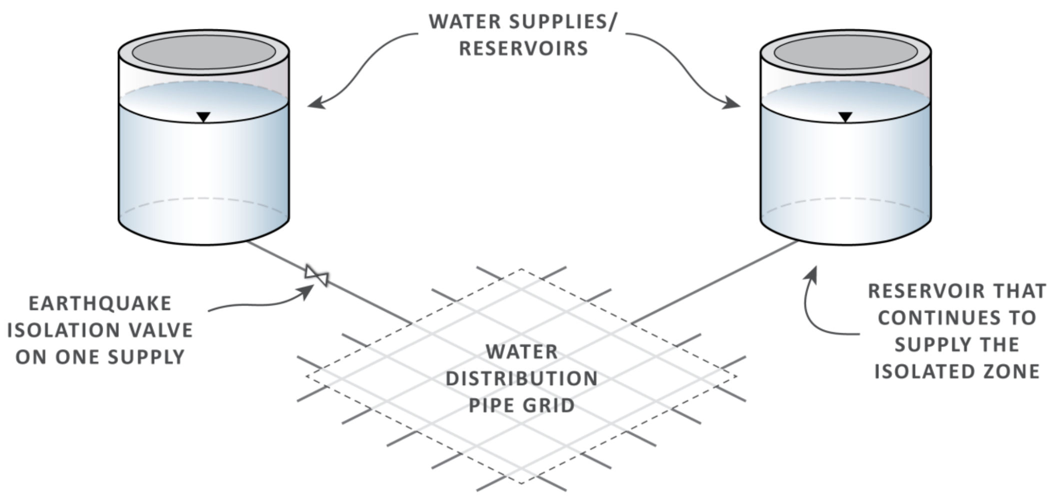

Figure 4. Typical water distribution system with two supplies/reservoirs, with one earthquake valve

Areas of the system with large storage volumes or served by a reliable/redundant supply will benefit less from tank isolation than areas without storage or reliable supplies. That is, it would take longer to lose service even if earthquake damage was causing a high demand. In some instances, the supply can keep up with the increased demand if there are a limited number of pipeline failures.

The consequence of loss of storage or supply should be considered from several different perspectives. First, if vulnerable areas are not isolated, they could drain adjacent areas making them unable to access water for fire suppression or for essential facilities such as hospitals. The flip side, however, is that areas that are isolated will lose service to support those same functions. Depending on the system post-earthquake operational strategy, areas with liquefiable soils resulting in extensive pipeline damage could be isolated within minutes with an automated valve following an event. However, this could cut off water to sprinkler systems and to critical facilities within the isolated area.

To address this concern, it is recommended that in areas where isolation systems are installed, redundant supplies be provided. These could include for example, redundant storage facilities or supplies (i.e., only isolating one), or providing an alternate supply for fire suppression such as from a nearby river or lake. One option would be to install a smaller diameter earthquake-resistant valve parallel to the larger isolation system, to allow some water through but to extend the time it would take before the tank drained. In some utilities, consideration is being given to installation of an independent highly reliable supply to critical facilities from a reliable source using a dedicated pipeline constructed with earthquake resistant pipe.

Manual Isolation Valves – These can be used to isolate pipeline leaks and breaks and can include: unplanned or planned isolation valve closure strategies or modifying the system configuration to minimize the number of valves. Manual isolation valves include those where the valve must be closed by turning a valve wrench or connecting a truck-mounted valve operator. These valves may already exist or can be new valves added to enhance the ability to isolate pipelines in emergencies or for general maintenance operations.

Most distribution system backbone pipelines have valves at connections to smaller diameter lines being fed from the transmission line (e.g., at street intersections). Backbone (or transmission) pipelines often have valves installed at regular intervals (e.g. several thousand feet) to isolate pipe sections for maintenance, or in the event of leaks or breaks. Some utilities are adding additional manually operated valves to enable them to isolate vulnerable pipe sections such as river crossings, locating valves as far back as 500 to 600 feet from the river, outside the liquefaction zone.

An example of a manually operated valve isolation system would be where a backbone pipeline running near a liquefiable area provides service to an essential facility such as a hospital (see Figure 5). Assume the backbone pipe has been upgraded with a welded steel pipe so as to be earthquake resistant but connects to older cast iron pipelines at each street intersection. When the earthquake occurs, the backbone pipe remains intact, but many of the connecting cast iron lines fail putting a large demand on the backbone pipeline. Operations crews would have to isolate every connection (12 valves in Figure 5) to the cast iron distribution grid to restore service to the hospital, possibly taking days following an earthquake. Alternatively, they could close the 14 valves required to isolate the liquefiable area.

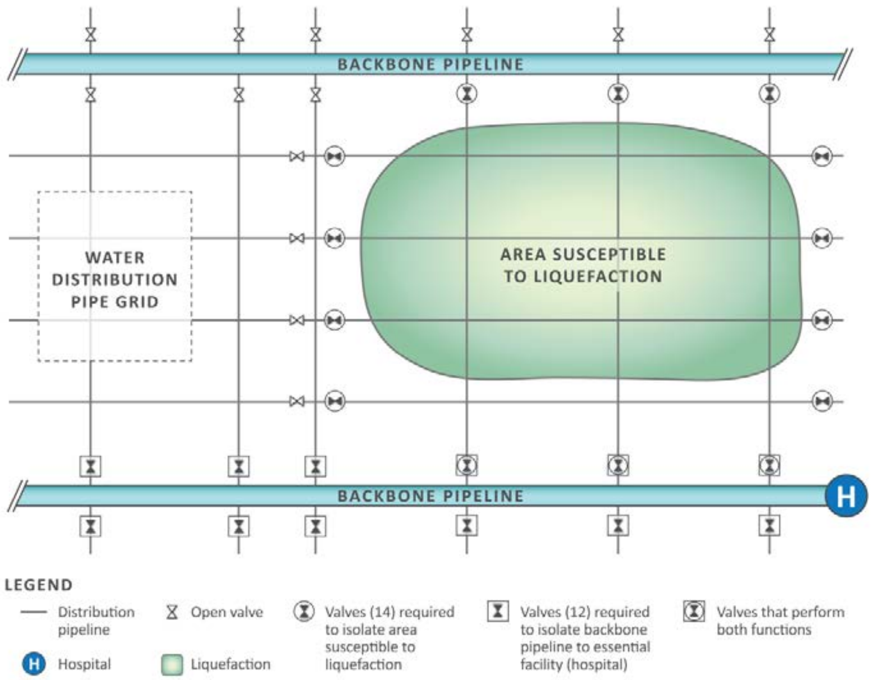

Figure 5. Valves along backbone pipeline in a typical distribution area

Manually operated systems are relatively inexpensive compared to remotely operated or automated valves, and there is no potential for false/nuisance valve closures. However it can take many hours to identify and locate the valves and dispatch a crew to close them, particularly in the post-earthquake environment. A valve isolation plan can be developed to identify valves that are required to isolate vulnerable areas and exercise them periodically to assure the valve functions properly when needed.

In some cases, manually operated valves have not been adequately exercised or maintained; in an emergency, when an attempt is made to close them, they may not operate, or they may not properly seat. Operations crews are then required to go back to the next set of valves to achieve isolation of an area. Similarly, in some cases, valves are “lost” by being paved over, and not adequately located on operations drawings. An aggressive valve exercising program can mitigate these problems.

In some cases, the distribution system can be modified to minimize the number of valves required to isolate vulnerable areas from the transmission/backbone system. Utilities have typically designed the layout of their distribution systems to minimize dead ends to enhance fire-flows and to maintain water quality. Unfortunately, this often results in numerous connections to backbone pipelines. After the 1995 Kobe earthquake, the Japanese pursued modified distribution system layouts to minimize the valves required to isolate sections of the system while maintaining fire-flows and water quality. In the example presented here, the 12 valves required to isolate the backbone pipeline to the hospital in Figure 5 could be reduced to just 4 valves in Figure 6. The arrangement in Figure 6 does not have any dead-end pipelines.

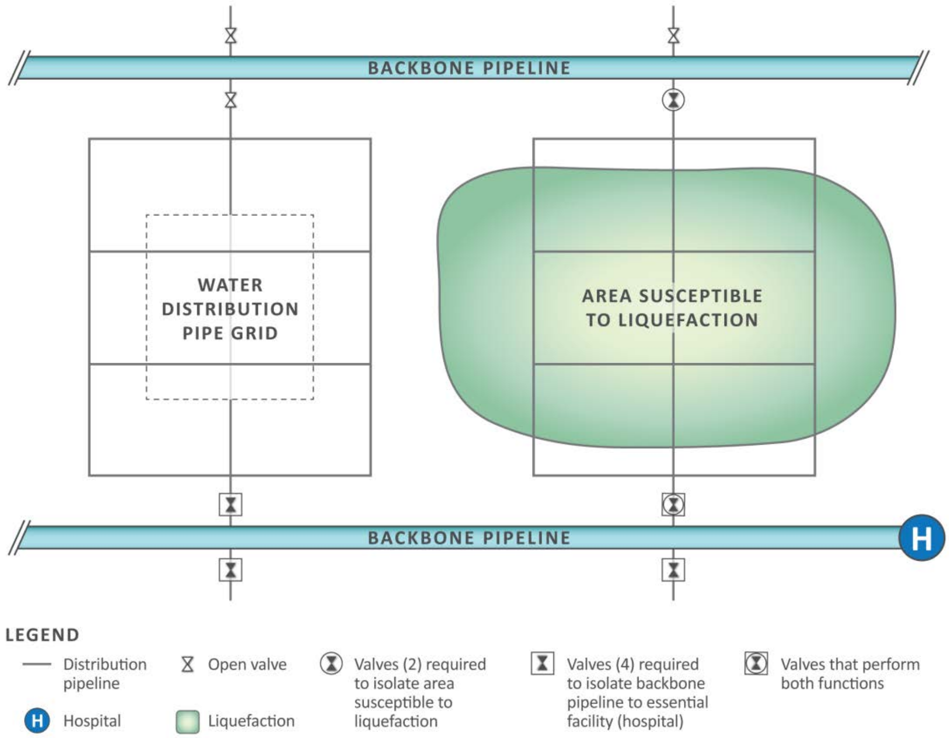

Figure 6. Arrangement in Japanese distribution system to minimize the number of isolation valves

Remotely operated or automated isolation valves can be used in place of manually operated valves to minimize the response time to isolate vulnerable/damaged areas following an earthquake. These valve installations are expensive and would typically be limited to key locations such as river crossings, reservoirs, and large areas geotechnically vulnerable to earthquakes.

To be remotely operated the valve must have a powered operator. Utilities typically prefer either electric motorized or pneumatic operators working in conjunction with a butterfly valve. There must be a backup power supply (typically batteries) for an electric operator, or a compressed air tank (with compressor) or nitrogen bottle for a pneumatic operator. This is all housed in a vault with a power supply. It is preferred to have a Supervisory Control and Data Acquisition (SCADA) connection and a programmable logic controller (PLC) giving the system operators the ability to monitor the flow and operate the valve remotely.

An alternative to the butterfly valve would be a globe valve typically configured as a pressure reducing valve. These can be plumbed to close using the upstream system pressure. The valve plumbing is configured with a small solenoid valve that would open or close the feed to control the valve position. A small battery would be the only power backup required to operate the valve.

Automated systems are sometimes used based on data from a local accelerometer (in terms of % of gravity acceleration) and a flow meter (e.g., inexpensive insertion paddle wheel type). The strategy would be to configure the PLC to evaluate the PGA and flow rate. If the PGA exceeded the set value, it would then check the flow rate to determine if there was significant downstream pipe damage (high flow rates) and close the valve accordingly. Supplemental data could be provided from geotechnical monitoring that could identify liquefaction PGDs. The operations staff could operate/override the valve position depending on the post-earthquake situation.

Legal and Social Issues

There is always a concern about shutting off the water supply (isolating) to some areas within the system. The benefit is to save water that would otherwise drain out through damaged pipelines resulting in the system becoming nonfunctional, but it could impact other critical water uses such as shutting off flow to a hospital or a manufacturing production line. These would be more of an issue in the event of a false/nuisance closure but should be considered in the planning of an isolation system.

One of the consequences could be loss of water for fire suppression. In Washington State, RCW 70.315 (Water Purveyors—Fire Suppression Water Facilities) exempts water utilities from liabilities associated with fire protection. However, it is recommended that utilities consider the legal implications of isolating/shutting off an area of the water system should fires ignite in the area.

It is also recommended that there be an alternate source of water available for firefighting, such as pumping from a lake, river, or marine waters, or having the capability to move water from an area without PGDs where isolation is less likely. These recommendations for providing an alternate supply may not be the responsibility of the water utility and should be communicated to the local fire authority(ies).

5.0 Seismic Retrofit and Replacement of Seismically Vulnerable Pipe as a Mitigation Measure

Seismically vulnerable pipelines can be mitigated by retrofitting them or replacing them to make them seismically resistant. Seismically vulnerable pipe can be readily identified by overlaying the pipe network on a hazard map. GIS is very useful in conducting this analysis. The pipe network layer should include the pipe material/joint. Designation of backbone (larger diameter) and distribution lines is also useful.

By analyzing GIS pipeline information along with seismic hazard data, as discussed in Section 2, pipeline damage can be estimated using methodologies/pipe fragilities such as those found in the American Lifelines Alliance, *Seismic Fragility Formulations for Water Systems*, 2001 that can be found online. Results can be estimated in terms of leak and break rates per unit length of pipe. This vulnerability information can be used, in conjunction with the importance/consequence of damage of the various pipelines to prioritize mitigation. The methodology is further described in the *National Institute of Standards and Technology Community Resilience Program, Guide Brief Number 4 – Determining Anticipated Performance* and *4A – Example for Determining Anticipated Performance.*

Approaches to seismically upgrade or replace pipe are discussed below.

Seismically upgrading pipe is possible but may be as expensive as replacing pipe. Upgrading pipe rather than installing new pipe adjacent to the existing pipe is most applicable where there is limited area; e.g., property/right-of-way constraints in the pipeline corridor, that require any mitigation be done to the pipe itself.

Water pipe has been slip-lined with both steel and HDPE, but these types of modified pipe have not been tested by being subjected to significant earthquakes.

Steel lining, for 36” and larger pipelines, can be designed to carry the full internal pressure and trench load. Joints are welded from the inside as there is no access from the outside, and the annular space is grouted so the lining and existing pipe work together as a composite structure. There are several limitations to this approach. First, a single weld has limited strength, and the pipe may be weak in tension. Welding both inside and outside or butt welding would be preferred but is probably not possible as there is no access from the outside. Second, grouting the annular space between the existing pipe and the liner limits the ability of the steel liner pipe to distribute pipe strain induced by PGD along the length of the pipe. For straight direct buried pipe, the strain can sometimes be distributed over several thousand feet. As a result, PGD deformation can result in large localized strains that could result in pipe damage. If the steel lining alternative is used, the strength of the composite pipe section should be evaluated against potential PGD and resulting pipe strains.

HDPE lining is very ductile and will provide some ability to span joints that are damaged. However, even if the annular space between the HDPE and existing pipe is not grouted, the water pressure will push the HDPE against the existing pipe wall, limiting its ability to distribute pipe strain along its length as determined by the Cornell Large – scale Lifelines Testing Facility (http://lifelines.cee.cornell.edu/) . Several options are available for HDPE lining: 1) using a thick wall designed to carry the full internal pressure, or 2) swaged installation with dependence of the existing pipe to carry some of the internal pressure. In either case, the HDPE may have some ability to span separated joints, particularly small “cracks” in leaded joints. Using thick wall HDPE can significantly reduce the pipe’s hydraulic capacity.

Both mortar lining and fiber/epoxy lining systems are brittle and are unlikely to significantly reduce the existing pipe’s seismic vulnerability.

Steel pipe with welded joints has been used because of its excellent seismic performance for decades. HDPE with fused joints has been used for the same reasons particularly for natural gas distribution systems. In the early 2010s, Kubota’s Earthquake Resistant Ductile Iron Pipe (ERDIP), manufactured in Japan, has been promoted in the US and installed on a pilot basis in major cities along the west coast. Several US manufacturers are now producing similar pipe in the US. Molecularly oriented PVC pipe (PVCO) (AWWA C-909) is well suited in areas subject to earthquakes because of its seismic resistance. It is highly ductile and is available with a seismic joint restraint system to control joint separation and an extra deep bell. Availability of seismic resistant fittings needs to be confirmed when its use is being planned. While PVCO has been in place for decades, it does not have the same life longevity experience of AWWA C-909.

New pipe systems should be selected to be seismically resistant to the seismic hazard environment they are being installed in, and to provide the level of service desired by the utility. While the International Building Code does not address pipeline design requirements, it does require that design of water system facilities that provide fire protection (e.g., tanks and some pump stations) be designed for a 2,475-year return earthquake. It can be inferred that distribution piping is required for fire suppression and should therefore also be designed for a 2,475-year event. To achieve this design level, the pipe should consider the guidelines discussed below.

Pipe installed in areas not subject to PGD.

- Critical pipe – continuous steel (with welded joints), HDPE with fused joints, or restrained joint ductile iron (RJ-DIP) or restrained joint molecularly oriented PVC (RJ MOPVC) (AWWA C909). For continuous steel, lap joints (bell and spigot joints) with a single weld, inside or outside, should be acceptable for areas not subject to PGD.
- Normal pipe – continuous or segmented steel, fused joint HDPE, bell and spigot DIP, or PVC (C900 or C909).

Pipe installed in areas subject to PGD

- Critical pipe – continuous steel (with double welded (in and out) or butt-welded joints), HDPE with fused joints, ductile iron pipe with seismic resistant pipe joints (American or Kubota), or molecularly oriented PVC with seismic resistant joint harnesses.
- Normal Pipe - continuous steel (with welded joints), HDPE with fused joints, ductile iron pipe with restrained joints or molecularly oriented PVC with extra depth bells.

Critical pipe is considered transmission and backbone piping plus pipe serving essential facilities such as hospitals.

6.0 System Restoration and Water Quality

Immediately following the earthquake, the system should be stabilized and a disinfect water notice sent out to all customers. Damaged pipe that is bleeding water from the system should be isolated. Consideration should be given to “shut off or not shut off” water for fire suppression area-by-area, and with consideration of service required to essential facilities.

System damage should be identified and documented to the extent possible, as damage to buried pipelines will not be fully evident until they are re-pressurized.

The pipeline repair operation should be initiated. Pipeline repairs should be prioritized considering two strategies:

1. Restore service to essential customers
2. Repair pipelines that will restore service to the largest number of users

One of the most time-consuming tasks during restoration is finding leaks. The line is pressurized, a leak discovered, the line shut down and drained, the leak repaired, and the process started over again. It is very difficult to start the restoration process in the distribution system until there is a reliable supply that can be used to pressurize the system.

Restoration of water quality will start with the supply, and then continue with the transmission piping, reservoirs, and the distribution system. Water quality should be restored as each transmission line or distribution pressure zone restoration is completed. It makes little sense to start water quality testing until pipelines in a pressure zone are completely repaired, as the water quality testing process must be performed each time the system is depressurized.

7.0 Long-Term Operation and Maintenance

To the extent possible, systems and facilities designed especially for mitigation of earthquake impacts should be integrated with day-to-day operation and maintenance functions. For example, mitigation relying on large diameter hose to bypass fault crossings may not be effective as the hose has to be stored and replaced on a regular basis; if it is not, it may fail when called on to perform. Also, it could require specialized equipment and/or up-to-date staff training or current contracts with a contractor. If those things aren't maintained, then hose deployment may fail even if inventory is up-to-date. Because of the long periods between earthquakes, these functions may otherwise be ignored.

No matter which mitigation strategies are used, the utility should be aware that they must be maintained in perpetuity. For example, in the Pacific Northwest, the Cascadia Subduction Zone earthquake has a 500-year return period. Currently seismologists estimate that there is a 15 percent chance it will rupture within the next 50 years. Planning must be updated on a regular basis, materials stored, and materials that deteriorate over time (e.g., gaskets, hose) replaced on a regular basis. Buried pipe is considered a permanent mitigation strategy and is only subject to deterioration from corrosion.

8.0 Emerging Tools from US Geological Survey

The USGS has developed/is developing two earthquake monitoring tools/services that may be beneficial to water utilities.

1. *ShakeMap/ShakeCast* - The USGS ShakeMap system monitors earthquake shaking intensities during the earthquake from monitors distributed across the region. The information from these is quickly gathered, mapped and distributed within a few minutes to end users on the USGS mailing list. The map shows the shaking intensity throughout the region. The USGS shaking intensity data can be augmented by monitors located at critical facilities within the end users system. The USGS has developed the ShakeCast tool to input the shaking intensity into a database of assets, and compares the asset's fragility to the measured shaking intensity. ShakeCast is setup and operated by the end user. The asset fragility information is developed by the end user (utility). ShakeCast then reports the expected performance of the various assets, e.g. no damage, slight, moderate extensive, collapse. This all happens within tens of minutes following the earthquake.This information can be combined with information from the utility SCADA system to determine the damage state of the various assets through the system, and help optimize crew response.
2. *ShakeAlert Early Warning System* - The USGS is developing the ShakeAlert system for the Pacific Northwest to quickly identify the occurrence of an earthquake and transmit that information to end users within seconds. The system will be particularly useful for the Cascadia Subduction Zone Earthquake (CSZ), as it is on the order of 100 miles distant; earthquake waves will take tens of seconds to reach the Seattle area. The time between the notification and the arrival of the wave can be used to stop activities and operating equipment that could be damaged by shaking.

9.0 Summary and Conclusions

Planning for and providing infrastructure to enable quick isolation of damaged pipelines and replacing seismically vulnerable pipelines are two strategies to mitigate earthquake pipeline damage.

Isolation systems can be manual, remote controlled or automated, and can be applied both to tanks and pipelines. Isolation of pipelines can be used to enable quick isolation of system elements having significant impact on the system such as river crossings or areas subject to liquefaction. Even manual isolation strategies can benefit post-earthquake system stabilization, if they are well planned. Some combination of manual and automatic/remote isolation is probably prudent.

Vulnerable pipelines can be identified and replaced with seismic resistant pipeline systems. Earthquake hazards can be mapped and spatially related to the piping systems using GIS. Planning tools such as those developed by the Americans Lifelines Alliance can be used to estimate pipeline failure rates and help prioritize which pipelines should be replaced. Pipeline replacement is expensive, so prioritization should be integrated with non-earthquake pipeline replacement programs carried out over a period of time.

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