Earthquake Resilience Guide for Water and Wastewater Utilities

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EARTHQUAKE RESILIENCE GUIDE
for Water and Wastewater Utilities

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Introduction
and Video

Step 1.
Understand the
Earthquake Threat

Step 2.
Identify Vulnerable
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Step 3.
Pursue Mitigation and
Funding Options

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Introduction and Video

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Introduction and Video

An earthquake is a sudden and violent shaking of the ground caused by movement within the earth's crust or by volcanic activity. While certain regions are more prone to seismic activity, earthquakes can occur anywhere in the country.

Earthquakes are difficult to predict and they may result in large-scale social and economic impacts.

Estimated Annualized Earthquake Losses for the United States. *Losses are increasing due to more development in earthquake-prone areas, vulnerability of older infrastructure and increased public and private sector interdependencies. Estimated losses are $6.1 billion per year with the largest in California (61%), Oregon and Washington (12%) and the central states (8%).*

The water sector is particularly vulnerable to earthquake damage and service disruptions. As stated in Resilience by Design from the Los Angeles Mayoral Seismic Safety Task Force, "the water system is the utility most vulnerable to earthquake damage, and that damage could be the largest cause of economic disruption following an earthquake."

By understanding the threat of earthquakes and the potential impacts to both the water infrastructure and the community, water utility owners and operators can make more informed decisions on earthquake mitigation options. While requiring financial investment, earthquake mitigation can significantly reduce or even prevent much costlier damages and economic impacts from future earthquakes. Also, the faster a water or wastewater utility recovers from an earthquake, the faster the community it serves can recover.

This guide helps water and wastewater utilities to be more resilient to earthquakes. It contains best practices from utilities that have used mitigation measures to address the earthquake threat. However, utilities should be cautious about proposing major seismic upgrades based solely on the information in this guide - a more detailed analysis is recommended. The guide is primarily meant to help:

- Utilities that know they are in earthquake-prone areas, but have not taken steps to address the hazard.
- Small and medium-sized utilities that need to better understand their seismic hazards.

There are three steps in this guide:

Step 1 - Understand the Earthquake Threat.
Step 2 - Identify Vulnerable Assets and Determine Consequences.
Step 3 - Pursue Mitigation and Funding Options.

Click the Surviving the Quake icon to watch a video about potential earthquake impacts to water systems.

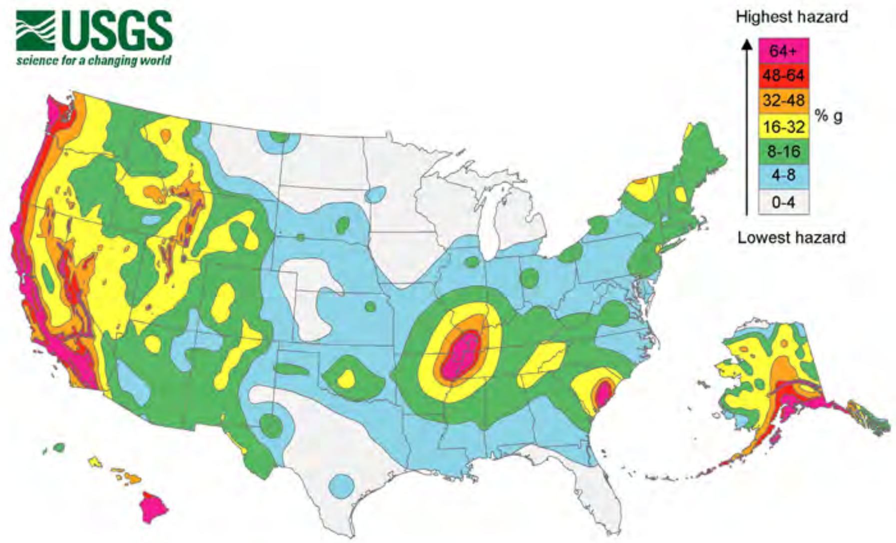
Earthquake Resilience Video

Step 1. Understand the Earthquake Threat

More than 143 million Americans, almost half the population of the United States, live in areas that are vulnerable to earthquakes.

- The western United States is particularly vulnerable due to a large number of faults or fractures in the earth's crust.
- In the central United States, the New Madrid Seismic Zone is a significant threat to at least eight states.
- In the eastern United States, earthquakes are smaller in magnitude; however, South Carolina has a significant seismic hazard.
- Both Alaska and Hawaii are prone to major earthquakes.

With thousands located across the country, many water and wastewater utilities are in earthquake hazard areas.



Is your Utility in an Earthquake Hazard Area?

- First, determine the earthquake threat to your utility. Use EPA's Earthquake Interactive Maps to locate your utility on the hazard maps.
- Then, contact your state hazard mitigation officer and work with your local mitigation planner. They may have already assessed and characterized your local earthquake hazard.

Click "Next" to learn about types of earthquakes.

Click for Earthquake Interactive Maps

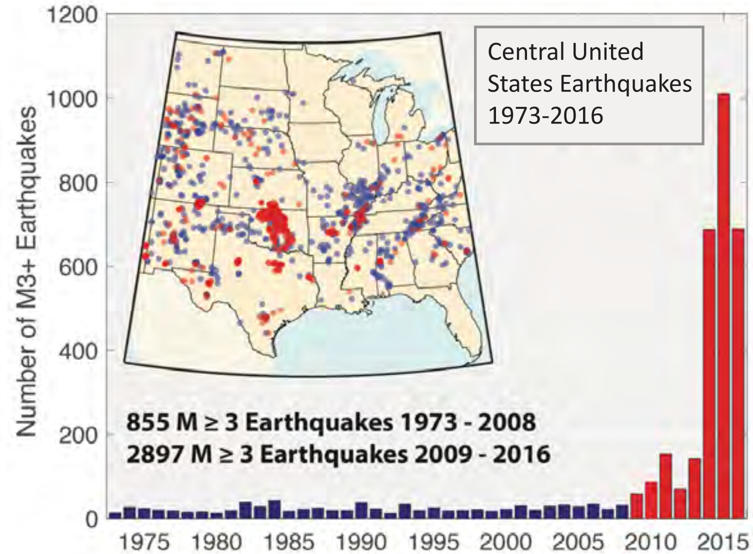
Step 1. Understand the Earthquake Threat

Types of Earthquakes

- **Natural Earthquakes.** Earthquakes occur on fault lines when rock bodies slip relative to each other. Seismic activity can happen deep in the earth or closer to the surface. The deepest earthquakes occur at subduction zones, where dense oceanic crust will sink, or subduct, under the lighter continental crust. Because of the large amount of seismic energy released at subduction zones, such earthquakes can shake the ground over many hundreds of miles. In contrast, crustal earthquakes are generally shallower. They can still cause intense shaking in more localized areas and are more likely to have fault displacement that ruptures the ground surface.

DETOUR
Learn about earthquake severity, or intensity scales

- **Induced Earthquakes.** Induced earthquakes are caused by human activity and may be triggered by such actions as impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gas from the subsurface and injection of fluids into underground formations. For example, when injected fluid finds its way to a stressed earthquake fault, the fluid can prompt fault movement and induce earthquakes. In the central United States, the number of earthquakes has increased dramatically since 2009 based on United States Geological Survey data. Typically, the seismic intensity of induced earthquakes is relatively small and not likely to cause much damage to water and wastewater utilities. However, larger and potentially damaging induced earthquakes have occurred in the past.



Natural and Induced Earthquakes > 3 Magnitude (USGS, 2016 data)

Click "Next" to learn about the types of ground movement that affect utilities.

Step 1. Understand the Earthquake Threat

Types of Ground Movement

- **Shaking and Ground Displacement.** Earthquakes are characterized by shaking that can damage structures. Shaking may be increased or amplified by the type of topography. For instance, ground shaking is worse in basins with soft sediments (e.g., Seattle) than in mountainous regions. If you know your utility is located on soft soils, damage may be worse than expected. The ground can also displace horizontally or vertically at the faults. This can cause surface ruptures and breaks in piping and other utility assets that cross these ground displacements.

- **Liquefaction.** When earthquakes occur in areas that are saturated and have loose, sandy soils (e.g., by rivers, lakes), the shaking can turn the ground to liquid. This phenomenon, called liquefaction, can be very destructive to your utility because buildings can sink into the liquefied ground. Buried drinking water pipes also will sink, however sewer pipes, manholes and pump stations (assets partially filled with air) may float to the surface. After the earthquake, the liquefied soil will re-solidify, locking tilted buildings and broken connections into place. To help identify potential liquefaction areas, use the liquefaction maps in EPA's Earthquake Interactive Maps or contact your state geological survey office.

Manhole floats from liquefaction

- **Lateral Spreading.** Lateral spreading is the sideways movement of liquefied soils on gentle slopes. This happens when liquefaction occurs in the subsurface layer, the movement of which can result in the opening of large fissures in the ground which can reach distances of several hundred feet. It can damage pipes, treatment facilities, wells, tanks and other water and wastewater assets. If the liquefied material is located far below the surface and there is a significant slope, the liquefied material and the ground surface can undergo significant down slope movement. This flow can particularly damage buried pipes and tanks.

- **Settling.** Earthquakes can cause the ground to change elevation and eventually settle. This is called ground subsistence and it can have serious impacts on water and wastewater systems, especially in locations dependent upon gravity flow. For example, in Christchurch, New Zealand, severe ground settlement of pipes prevented the proper flow of sewage.

DETOUR
Learn about other earthquake hazards

Step 2. Identify Vulnerable Assets and Determine Consequences

Water and wastewater utilities are particularly vulnerable to earthquakes because of the extensive network of above and below ground pipelines, pump stations, tanks, administrative and laboratory buildings, reservoirs, chemical storage and treatment facilities.

For a drinking water system, an earthquake can cause hundreds … even thousands … of breaks in water pipelines, ruptures in storage and process tanks and the collapse of buildings. This can cause a loss of water system pressure, contamination and drinking water service disruptions for your customers.

A wastewater system can also expect infrastructure damage from an earthquake, including breaks in the collection system. Sewers and wastewater treatment plants tend to be built on ground which is subject to liquefaction. Damage can lead to sewage backups in homes and potential releases of untreated sewage into the environment.

To protect your utility, you will need to assess the potential damage to buildings and key assets. This step is broken into three actions:

- Action 1 – Inventory critical assets and plot them on hazard maps.
- Action 2 – Characterize critical assets, types of failures and consequences to your utility.
- Action 3 – Summarize results and prioritize mitigation.

Learn about assessment tools

Click "Next" to learn more about these three actions.

Ultimately, these actions will help you determine the types of mitigation measures and strategies that are worth considering. However, you still may require technical expertise and analysis from other professionals. State agencies, other utilities, consultants and free assessment tools may be helpful.

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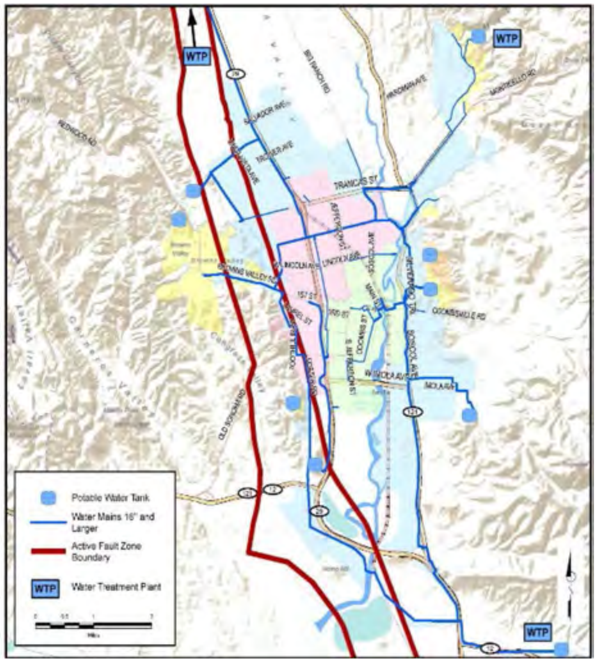
Step 2. Identify Vulnerable Assets and Determine Consequences

Action 1 – Inventory Critical Assets and Plot on Hazard Maps

List and plot the location of your key assets on a seismic hazard map. Locate the assets relative to earthquake threats, including shaking, surface faults and liquefaction.



Assets on Hazard Map

Action 2 – Characterize Critical Assets, Types of Failures and Consequences to Your Utility

Characterize your building structures, pipelines, tanks, reservoirs, pumps, lift stations, wells, treatment facilities and power assets to determine their vulnerability. Note that the construction materials, design or age can make an asset particularly vulnerable. Other factors to consider when assessing possible asset failures and the consequences to your utility include:

- Potential for loss of power.
- Direct hazard to employee and public safety.
- Possible gas line ruptures and fires near utility assets.
- Impacts to firefighting and hospitals.
- Time for repairs.
- Availability and cost of spare parts.
- Need to provide emergency drinking water or alternate wastewater services.

Click “Next” to see how to characterize the vulnerability of your buildings and pipelines and then click “Next” again for tanks and reservoirs, pumps, lift stations and wells, treatment facilities and power assets.

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Step 2. Identify Vulnerable Assets and Determine Consequences

Action 2 – (continued)

2a) Characterize Buildings. Characterize the age and construction type of your buildings to determine their vulnerability to earthquakes. Note that building failure and collapse are critical dangers to your personnel. See the table to the right for summary information relating anticipated earthquake damage to building construction type (see Association of Bay Area Governments Resilience Program). Also, consult the American Society of Civil Engineers (ASCE) Standard 41-06 Seismic Rehabilitation of Existing Buildings (2007). In general, buildings older than 1995 are more vulnerable to earthquake damage.

Building Structure	Anticipated Damage
Unreinforced masonry	Severely cracked or collapsed walls. Separation between floors and walls jeopardize vertical support of roof and floor systems, leading to collapse
Unreinforced brick	Substantial damage
Tilt up concrete	Connection between the roof and walls can fail causing roof collapse
Non-ductile concrete frame	Lateral movement can strain frame with catastrophic consequences
Non-Structural elements (cladding)	Detach from building injuring people and impeding evacuation or access

2b) Characterize Pipelines. Characterize pipelines to determine vulnerability to earthquakes. Consider factors including pipe location, age, compatibility with soils, construction materials and number of joints. From ground shaking, pipes often crack at brittle joints or are crushed at the bell or pipe barrel. From liquefaction or lateral spreading, pipes often break or separate at the joints. For example, in the Kobe, Japan earthquake, more than half of the drinking water pipe failures were from joints pulling apart.

Crushed pipe

Drinking water pipes are commonly made with ductile iron (DI) (historically cast iron), welded steel, polyvinyl chloride (PVC), pre-stressed concrete or asbestos cement. Cast iron pipes have the highest break rate in both liquefaction and non-liquefaction areas. Asbestos cement pipes are known to have moderate to high vulnerability, especially in liquefaction areas.

Learn more about pipe vulnerability

Wastewater pipes are more prone to damage than drinking water pipes, however in terms of function, damaged sewer pipes may still be operational with some leakage. Wastewater pipes are typically made of reinforced concrete, PVC, vitreous clay and fiberglass. Such pipes and manholes may buoyantly float in liquefied soils, causing severe problems.

In general, pipelines are prone to failure at connections to aboveground structures, such as reservoirs, treatment plants, pump stations and at bridge or fault crossings.

Step 2. Identify Vulnerable Assets and Determine Consequences

Action 2 – (continued)

2c) Characterize Tanks and Reservoirs. Damage to storage tanks can occur from the actual shaking as well as the permanent ground deformation caused from liquefaction, landslides, etc. Types of damage include sliding on the foundation, elephant foot buckling for steel tanks, stretching of bars for wood tanks or cracking or shearing of walls for concrete tanks. Also, liquids in tanks or reservoirs can slosh and create forces on tank walls beyond the design capacity. In the 1994 Northridge earthquake, movement of a water tank caused the piping to sever. A steel tank at a utility in Los Angeles suffered elephant foot buckling from sloshing.

Severed pipe

Elephant foot buckling

2d) Characterize Pumps, Lift Stations and Wells. Pay particular attention to wastewater pump stations and booster pumps in liquefiable soils as they often float, which severs connecting piping. An inoperable lift station can cause wastewater to overflow and backup into residences and commercial buildings. Manholes may also float. For wells, ground movement, including liquefaction-induced lateral spreading, can bend casings, distort vertical shafts and disable well pumps.

2e) Characterize Treatment Facilities. Treatment structures at water and wastewater utilities have a wide variety of equipment, processes and chemicals. Wastewater treatment buildings tend to be near rivers in areas subject to liquefaction. Also (as in the 1989 Loma Prieta earthquake in California), clarifiers can be heavily damaged due to sloshing wastewater. In another example, an earthquake created a chemical spill that entered the collection system of a wastewater utility, which then caused the biological treatment process to fail. Coupled with the loss of power to the blowers, the secondary treatment system was inoperable for several weeks.

Damaged clarifier

2f) Characterize Power Assets. Maintaining electric power is key for both water and wastewater operations. Earthquake damage to power lines, transformers, generators and feeds will disrupt equipment functionality. Assets from both the power utility and the water and wastewater utility need to be assessed for possible failure and restoration.

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Action 3 – Summarize results and prioritize mitigation

After completing Actions 1 and 2, summarize your asset vulnerability and consequences in a simple table such as the one below. Then, determine the "Priority for Mitigation" (last column) based on your best professional judgment and advice from government or private sector experts.

Critical Asset or Resource	Sample Evaluation Factors												Priority for Mitigation		
	Subject to liquefaction	Not seismically protected	May endanger employees	Close to earthquake fault	In earthquake hazard zone	Reliant on grid power	Materials, design or age make asset vulnerable	Impacts firefighting ability	Critical for clean water and sewage treatment	Enhances response and/or recovery	Failure may endanger public	Consequence	Low	Medium	High
Pump #5		✓		✓	✓	✓						Pump is the backup for Pump #6. Loss of pump could be handled by…		✓	
Cast iron pipe near treatment facility	✓	✓			✓		✓	✓	✓			Cast iron pipes fail at joints to above-ground buildings. Result in loss of system pressurization. No drinking water for weeks and limited water available for firefighting.			✓
Occupied building #1		✓	✓		✓	✓			✓			Building could collapse and endanger workforce.			✓

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Consider mitigation actions and projects to help your utility better withstand an earthquake, minimize damage and rapidly recover from disruptions to service. An example is to replace vulnerable buried pipe with seismic resistant pipe. Such efforts can be part of a long term capital improvement and asset management plan. As one strategy, when you replace aging equipment after its design life, install seismic upgrades, which are typically not major added costs.

Mitigation Options

Fortunately, many utilities have evaluated the threat of earthquakes and taken actions to mitigate damage. Explore some of these mitigation approaches, including several low cost options.

Mitigation for Immediate Life Safety

Mitigation for Key Systems in Hazard Areas

Mitigation through Emergency Response

Mitigation by Specific Asset

Learn more about mitigation from other sources

Learn more about seismic building codes

Funding Options

Utilities have many options to implement and fund earthquake mitigation projects. Click Funding Options:

Funding Options

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Mitigation for Immediate Life Safety

✓	Mitigation Options	Cost
	1. Protect your employees	
	a. Make sure employees know your emergency response plans and practice emergency action drills.	$
	b. Maintain emergency generators (seismically certified) at employee locations to help mitigate widespread power outages.	$$
	c. Prevent collapse of occupied buildings. For seismic protection of new buildings, follow ASCE 7 Standard Minimum Design Loads for Buildings. To retrofit buildings (e.g., bracing or shear walls), follow ASCE 41-06 Seismic Rehabilitation of Existing Buildings.	$$$
	d. Anchor equipment (e.g., computers, bookshelves) as well as laboratory equipment and chemical and fuel tanks.	$
	e. Identify people who can perform post-earthquake building inspections for safety.	$
	2. Protect the public from catastrophic failures of vulnerable storage tanks or reservoirs	
	a. Seismically retrofit water tanks (e.g., anchoring to foundations).	$$$
	b. Strengthen concrete tank walls, replace non-flexible connections and improve roof structures over large reservoirs.	$$$
	c. For new tank installations in high risk seismic zones, determine if liquefaction or other permanent ground movements are possible. If so, stabilize the foundation to minimize movement. Design the tank height to safely account for sloshing forces during an earthquake.	$$$
	3. Plan for emergency public health and firefighting	
	a. Work with your community and state on an emergency plan for drinking water and sewage treatment (e.g., improvised chemical toilets).	$
	b. Develop a plan for emergency sewage capability, including portable or improvised chemical toilets.	$
	c. Plan for use of temporary bypasses to move wastewater flow away from the public following ground movement.	$$
	d. Address high consequence sewers like those that are difficult to repair (e.g., under rivers, highways or buildings).	$$$
	e. Coordinate with firefighters on a plan to obtain alternate water supplies like swimming pools, reclaimed water and seawater.	$

Cost Key (Ranks relative costs of mitigation measures - actual costs may differ for your utility)
$ - Little to no cost. Some internal level of effort required, but no contractor support needed.
$$ - Moderate cost and complexity. Likely involves contractual costs.
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Mitigation for Key Systems in Hazard Areas

✓	Mitigation Options	Cost
	1. Reinforce "backbone" of your utility (e.g., treatment facilities, transmission lines, large diameter pipelines and storage tanks)	
	a. For a water system, consider installing isolation valves on main transmission lines. For pipes in areas with a moderate to high liquefaction hazard or that traverse active faults, replace with pipes designed to the specifications in Seismic Guidelines for Water Pipelines (ALA, 2005). In general, use steel with welded joints, high-density polyethylene (HDPE) pipes with fused joints, ductile iron with seismic joints and molecularly oriented PVC (PVCO) with restrained joints (American Water Works Association C909 PVCO Pressure Pipe, 4 In. through 24 In., for Water, Wastewater, and Reclaimed Water Service; 2010).	$$$
	b. Design the backbone of your utility to supply water to critical facilities (e.g., hospitals and fire suppression points). This strategy might require special points of distribution or other ways to deliver water from the backbone. Also, consider quick fixes (e.g., temporary piping to maintain capability) in the short term as you wait for completion of expensive mitigation projects that may take years to implement.	$$-$$$
	c. For a wastewater system, seismically harden major trunk lines and pump stations.	$$$
	2. Address liquefaction areas and fault lines	
	a. Consider options to protect fixed water system assets, including improving soils with soil mixing, cement grouting, stone columns, piles, compaction or movement of assets into non-liquefaction areas. Consult geotechnical engineers and engineering geologists experienced in liquefaction hazard mitigation.	$$$
	b. Position drinking water wells outside of seismic hazard zones if possible.	$$$
	c. Require mitigation for key pipelines that cross known and active fault lines. Consider installing a bypass or temporary emergency pumping systems as well as replacing hard (inflexible) tank joints with soft (flexible) or ball joints to limit breakage.	$$$

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Step 3. Pursue Mitigation and Funding Options

Mitigation through Emergency Response

✓	Mitigation Options	Cost
1.	Plan for Response	
	a. Develop an emergency response plan (ERP) that includes procedures for earthquakes.	$-$$
	b. Ensure that employees are trained on the ERP and periodically exercise its procedures to maintain an acceptable level of readiness. Also, train workers in the incident command system so that utility responders can better coordinate with other local and state responders. Participate in community-wide earthquake preparedness training and exercises.	$
	c. Consider back-up locations for your Emergency Operations Center and back-up systems for emergency communications (e.g., 800 MHz radios)	$$
	d. Consider preparing emergency “Go Kits” for employees and their families.	$
	e. Establish and maintain a current list of key contacts and phone numbers for local agencies, contractor services support, material supply vendors and interdependent services within the community.	$
	f. Coordinate earthquake preparedness activities with interdependent services within the community, such as power providers, and with critical customers, such as hospitals and major commercial entities.	$
2.	Maintain Assets for Response	
	a. Have adequate spare parts (e.g., temporary piping, pre-made hose bibs and hydrant cable connections), equipment and certified, trained staff to rapidly fix damage after an earthquake.	$$
	b. Address how power will be restored to pump stations (e.g., permanent or portable generators, portable pump connections and whether to own, share or contract fuel trucks for generators).	$$-$$$
	c. Join a mutual aid network like the Water and Wastewater Agency Response Network (WARN). During the Napa earthquake, the Napa water utility used the California WARN to request seven teams from other utilities to help repair pipelines.	$
	d. If appropriate, maintain a fleet of small water tanker trucks or water buffaloes and the fuel needed to operate them.	$$

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Step 3. Pursue Mitigation and Funding Options

Mitigation by Specific Asset

Click a photograph below and get information on specific earthquake mitigation options for that asset.


Pipes


Buildings


Treatment Facilities, Pumps, Lift Stations and Sewers


Basins, Reservoirs and Impoundments


Above Ground Storage Tanks


Power Supply and Electrical Components


Wells, Source Water and Dams

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Mitigation for Pipes

✓	Mitigation Options	Cost
1. Above Ground Pipes		
	a. Brace pipes with ties or other methods; provide flexibility and connections to hard points.	$$
2. Underground Pipes – Non Liquefaction Areas		
	a. Use modern pipe (e.g., DI, PVC) which is typically adequate for areas with small to moderate ground motions and no permanent ground deformation.	$$
	b. Replace vulnerable transmission and backbone piping first before distribution piping. For vulnerable pipelines, consider installing redundant pipes in locations with less seismic activity.	$$$
3. Underground Pipes – Liquefaction Areas		
	a. Use seismic resistant pipe such as steel with welded joints, HDPE with fused joints, DI with seismic joints or molecularly oriented PVC with restrained joints (AWWA C909) for transmission pipelines subject to ground deformation from liquefaction and landslides.	$$
	b. Slip line existing pipe with HDPE to decrease the pipe's vulnerability.	$$
	c. Replace pipes in accordance with Seismic Guidelines for Water Pipelines (ALA, 2005) in areas with moderate to high liquefaction or that traverse active faults.	$$$
	d. Consider changing pipe alignment to avoid liquefiable areas or replace with new pipe. Intake pipes are often susceptible to liquefaction. Stabilization of soils (e.g., deep soil mixing and stone columns) is possible, but expensive.	$$$
	e. Install portable facilities (e.g., hoses, pumps) to allow pipelines to bypass areas of liquefaction.	$$

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Mitigation for Buildings

Follow ASCE 7 for new buildings and ASCE 41-06 for retrofitting of buildings. Retrofits could be accomplished by adding new seismic bracing or shear walls. Do not forget to anchor equipment within buildings (e. g., computers, bookshelves and vending machines). You can find additional suggestions in the Association of Bay Area Governments Resilience Program or ASCE 41-06.

✓	Mitigation Options	Cost
1. Unreinforced Masonry Buildings		
	a. Tie walls to floor and ceiling elements or anchor unsupported masonry walls, install bracing or apply wall overlays to add strength.	$$$
2. Non-Ductile Concrete Frame Buildings		
	a. Add interior walls or jacketing or wrap concrete structural columns for strength and ductility.	$$$
3. Tilt-up Concrete Building		
	a. Bracket the walls to the roof.	$$

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Mitigation for Treatment Facilities, Pumps, Lift Stations and Sewers

✓	Mitigation Options	Cost
	1. For Both Liquefaction and Non Liquefaction Areas	
	a. Anchor or brace pumps, process and lab equipment.	$
	b. Maintain seismically certified (see the International Building Code) emergency generators at key facilities to help mitigate widespread power outages.	$$
	2. For Liquefaction Areas	
	a. Consider mitigation approaches, including improving soils with soil mixing, cement grouting, stone columns, compaction and piles for treatment facilities. Piping associated with treatment facilities may also benefit from these strategies.	$$$
	b. Provide flexible connections for pipeline connections to pump stations.	$-$$
	c. Consider what design might be best for new sewers in liquefiable soils, as sewers and manholes will float during an earthquake. HDPE with tie downs is one alternative, another is adding concrete to manholes to reduce their buoyancy.	$$

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Mitigation for Basins, Reservoirs and Impoundments

✓	Mitigation Options	Cost
	1. For Both Liquefaction and Non Liquefaction Areas	
	a. Reinforce concrete structures, strengthen concrete tank walls, use flexible connections to pipes (e.g., ball joints) and improve roof structures over large reservoirs.	$$$
	b. Strengthen reservoirs by buttressing basin walls.	$$$
	c. Increase capacity for buried, seismically-protected drinking water storage. Consider redundancy of these assets for the short term, but you will need to evaluate cost effectiveness.	$$$
	d. Replace hard (inflexible) tank joints with soft (flexible) joints to limit breakage especially where tank wall uplift is anticipated (e.g., unanchored tanks).	$$
	e. Anchor older pre-stressed concrete tanks with seismic cables.	$$
	f. Use AWWA Standards D100-10 (Welded Carbon Steel Tanks for Water Storage, 2010) D110-13 (Wire and Strand Wound, Circular, Prestressed Concrete Water Tanks, 2013) and D115-06 (Tendon Prestressed Concrete Water Tanks, 2006). For concrete tanks and basins, use ACI 350-06 (Code Requirements for Environmental Engineering Concrete Structures, 2006).	$

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Mitigation for Above Ground Storage Tanks

✓	Mitigation Options	Cost
1. Water Tanks		
	a. Conduct site-specific subsurface investigations for new tank installations in high seismic zones to determine the potential for permanent ground movements. If the site has a moderate to high potential for movement, use steel tanks rather than concrete unless the hazard is mitigated.	$$$
	b. Reinforce the foundation on large horizontal tanks. Some unanchored tanks will sustain damage where they connect to fixed piping.	$$$
	c. Consider automatic shutoff valves on tanks. Use only on tanks in pressure zones with multiple reservoirs and feeds.	$$
	d. Seismically retrofit water tanks, which can include anchoring to foundations, strengthening concrete tank walls, replacing non-flexible pipe connections and improving roof structures over large reservoirs.	$$$
2. Chemical Tanks		
	a. Anchor or restrain chlorine containers and chemical tanks.	$

Cost Key (Ranks relative costs of mitigation measures - actual costs may differ for your utility)
$ - Little to no cost. Some internal level of effort required, but no contractor support needed.
$$ - Moderate cost and complexity. Likely involves contractual costs.
$$$ - High cost and complexity. Will require one or more contractors to implement this option.

Step 3. Pursue Mitigation and Funding Options

Mitigation for Power Supply and Electrical Components*

✓	Mitigation Options	Cost
	1. Power Supply	
	a. Consider purchasing or renting seismically-certified backup power generators. Fixed generators and associated systems must be anchored.	$$
	b. Have portable generators available to dispatch with capacities determined and plug-ins designed for specific facilities.	$$
	c. Test emergency power options regularly.	$
	d. Communicate with your power company to prioritize electricity restoration to water and wastewater utilities.	$
	2. Electrical Components	
	a. Add electrical redundancy at treatment plants. Note that multiple feeds may come from the same high voltage substation, which may itself be vulnerable to earthquakes.	$
	b. Install new anchorages for transformers and reroute electrical boxes.	$$

*Refer to Power Resilience Guide for Water and Wastewater Utilities for additional suggestions.

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Step 3. Pursue Mitigation and Funding Options

Mitigation for Wells, Source Water and Dams

✓	Mitigation Options	Cost
1. Wells		
	a. Consider locating wells outside of seismic hazard zones. Wells are vulnerable if exposed to ground deformation from liquefaction, fault activity and landslides.	$$-$$$
	b. Design the upper casing (approximately 40 feet) to resist all imposed loads due to liquefaction and/or lateral spread.	$$
	c. Use stainless steel screens rather than slotted casings to avoid corrosion failures that can result in a loss of capacity or water quality issues.	$$
	d. Provide well discharge piping with the ability to accommodate differential settlement between the well head and buried pipe.	$$
2. Source Water		
	a. Explore a diversity of water sources (e.g., river, groundwater or reservoir) and associated supporting facilities. Certain water sources may be more vulnerable to earthquakes.	$$-$$$
3. Dams		
	a. Assess dam vulnerability with an expert. The consequence of dam failure can be very high in terms of public safety.	$$$

Cost Key (Ranks relative costs of mitigation measures - actual costs may differ for your utility)
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$$ - Moderate cost and complexity. Likely involves contractual costs.
$$$ - High cost and complexity. Will require one or more contractors to implement this option.

Step 3. Pursue Mitigation and Funding Options

Funding Options

Become Eligible for Funding by Joining Local Mitigation Efforts. Local governments are required to develop hazard mitigation plans and have strategies in place to mitigate the effects of natural disasters, including earthquakes. Be sure that local mitigation plans include language about mitigating earthquakes at your utility so that proposed mitigation projects become eligible for federal funding. Also, adopt seismic design standards for new facilities, so that if the facility is damaged in an earthquake, the Federal Emergency Management Agency (FEMA) will reimburse you to the adopted standard. How can you partner with your local mitigation planner? Check out EPA's Hazard Mitigation Guide for Natural Disasters.

Federal Funding for Mitigation Projects. Receiving federal funding for an earthquake mitigation project often requires diligence, good connections with local mitigation planners and a strong application. To help utilities understand and obtain federal disaster and mitigation funds, EPA developed Fed FUNDS. Fed FUNDS can help you quickly screen for applicable funding programs from FEMA, EPA, the United States Department of Housing and Urban Development (HUD), the United States Department of Agriculture (USDA) and the Small Business Administration (SBA). It also provides examples of successful utility applications and tips to get funding.

Utilities in Utah became involved in their local hazard mitigation process and ended up receiving significant FEMA and Bureau of Reclamation funds for earthquake mitigation.

FEMA has three individual programs to fund mitigation projects for earthquake resilience:

- Public Assistance (PA) Grant Program.
- Hazard Mitigation Grant Program (HMGP).
- Pre-Disaster Mitigation (PDM) Program.

Each program has specific project eligibility and funding requirements. Typically, the proposed mitigation projects must go through a benefit-cost analysis and show clear benefits. See the FEMA STAPLEE Method for a formal benefit-cost review used for FEMA funded projects.

When evaluating the mitigation approaches, consider:

- *Effectiveness in mitigating asset damage.*
- *Practicality in implementing mitigation options.*
- *Costs, including capital, operations and maintenance.*

Step 3. Pursue Mitigation and Funding Options

Funding Options

Develop a Plan to Implement Earthquake Mitigation Projects. The plan should identify the actions to implement the project, the time to complete the project, the lead person or agency responsible for taking the actions and the costs and funding sources (e.g., grant funds or capital expenditures). The plan should reflect a long-term commitment to the project. Depending on the size, cost and complexity, some mitigation actions may be completed through internal work orders, capital improvement planning or supplemental funding. The use of multiple funding sources is an effective strategy. See a sample mitigation project plan below.

Mitigation Project	Actions to Implement Mitigation Project	Time to Complete	Lead Individual or Agency	Funding Source
Seismic Retrofit of Water Tanks	• Develop proposal that outlines basic engineering plans and a benefit-cost analysis to retrofit tanks (2 months). • Incorporate project into local hazard mitigation plan and capital improvement budget (3 to 10 months). • Take proposal to town manager for preliminary approval (4 months). • Work with local mitigation official and pursue FEMA mitigation funds (4 months to 1 year).	1 year	Operations and Financing	Capital improvement funding and FEMA HMGP
Seismic Emergency Power Generator	• Develop proposal that outlines basic engineering plans and a benefit-cost analysis for a seismic generator (note benefits for other disasters); include costs for operations, maintenance and fuel (2 months). • Talk to power utility about priority restoration of electricity as well as possibility of a generator (2 to 3 months). • Talk to fuel vendors to establish agreements (within 2–3 months). • Take proposal to town manager for preliminary approval (4 months). • Work with local mitigation official and explore idea of getting FEMA mitigation funds for generator, perhaps bundled with other measures (4 months to 1 year).	1 year	Operations and Financing	Capital improvement funding and FEMA HMGP

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Measuring Earthquake Severity

Modified Mercalli Intensity Scale

Scale ranging from I to XII based on damage at a particular location. The more the damage, the higher the number.

Intensity	Shaking	Description and Damage
I	Not felt	Not felt.
II	Weak	Felt only by people sitting or those on upper floors of buildings.
III	Weak	Felt by almost all persons indoors. Hanging objects swing. Vibrations felt similar to the passing of a truck. May not be recognized as an earthquake.
IV	Light	Felt by all indoors and a few outdoors. Some awakened at night. Stopped cars rock. Windows, dishes and doors rattle. Glasses clink. In the upper range of IV, wooden walls and frames creak.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes and windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all. People walk unsteadily. Windows crack. Dishes, glassware, knickknacks and books fall off shelves. Pictures fall off walls. Furniture moved or overturned. Weak plaster, adobe buildings and some poorly built masonry buildings crack. Trees and bushes shake visibly.
VII	Very strong	Difficult to stand or walk. Noticed by drivers in cars. Damage to poorly built masonry buildings. Weak chimneys broken at roof line. Plaster, loose bricks, stones, tiles, cornices, unbraced parapets and porches fall. Some masonry buildings crack. Waves on ponds.
VIII	Severe	Steering of cars affected. Extensive damage to unreinforced masonry buildings, including partial collapse. Some masonry walls collapse. Chimneys twist and fall. Wood-frame houses moved on foundations if not bolted; loose partition walls thrown out. Tree branches broken.
IX	Violent	General panic. Damage to masonry buildings ranges from collapse to serious damage unless modern design. Wood-frame structures rock and, if not bolted, shift off foundations. Underground pipes broken. It is also likely that pipes are broken at lower intensities.
X	Extreme	Some well-built wooden structures and bridges destroyed; most masonry and frame structures destroyed with their foundations. Rails bent. Poorly built structures destroyed with their foundations.
XI		Rails bent greatly. Underground pipelines completely out of service.
XII		Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Richter Scale*

Magnitude	Strength of Earthquake
3-3.9	minor
4-4.9	light
5-5.9	moderate
6-6.9	strong
7-7.9	major
8+	great

*Logarithmic measure of total energy (magnitude) released at epicenter (point on earth's surface directly above where earthquake starts). Scale does not relate to damage.

Moment Magnitude

- logarithmic measure of energy release.
- function of the length, width and fault offset.
- replacing Richter Scale.

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Learn More about Earthquake Hazards

Below are other hazards that can accompany earthquakes. Also, the United States Geological Survey has a wealth of information on earthquakes.

Tsunamis. In the ocean, an earthquake may generate significant tsunamis (huge waves of water) that can severely damage your coastal infrastructure. Tsunamis can be generated from displacement of faults under the ocean or from generation of large landslides. For example, an earthquake at the Cascadia subduction zone could cause a tsunami off the coasts of Oregon, Washington and northern California. One study looked at flood inundation and evacuation maps for two small coastal towns in Oregon. Tsunamis can also strike coastal states even though they may be generated by earthquakes in other states and countries.

Computer modeling of a tsunami after a hypothetical magnitude 7.8 earthquake on the Cascadia subduction zone.

Landslides and Rockfalls. Shaking can trigger landslides and rockfalls. Both can damage aboveground utility structures as well as buried pipelines.

Flooding. Earthquakes can damage dams and reservoirs that can potentially release floods that can threaten populations and damage infrastructure.

Fires. Outbreaks of fires often accompany earthquakes. This presents a potential challenge when fires are near utility assets as well as an added responsibility of the utility to maintain water availability for firefighting.

Tools to Assess Your Specific Structures

If you want to perform a seismic analysis of your specific structures (e.g., treatment buildings, biosolids building, administration building, electrical controls), there are free tools to help, but it may take some time and experience to use them.

FEMA Hazus - Contains models for estimating potential losses from earthquakes, floods and hurricanes. Hazus uses Geographic Information Systems (GIS) technology to estimate physical, economic and social impacts of disasters. Chapter 8 of the Technical Manual for Earthquakes Model focuses on direct damage to water utilities and wastewater utilities as well as estimated restoration time.

ROVER - Rapid Observation of Vulnerability and Estimation of Risk, is FEMA's free mobile software to inventory buildings (including location) and help building managers prioritize evaluation and rehabilitation after an earthquake.

ShakeCast and **ShakeMaps** - During earthquake response, these free USGS software products predict damage to your buildings from actual earthquakes and notify you so that you can take quick actions to ensure safety and restore your utility. For earthquake planning, ShakeMaps has earthquake scenarios that you can use to determine the potential damage to your buildings.

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Pipe Vulnerability

Pipe Material Type and Diameter	AWWA Standard	Joint Type*
Low Vulnerability		
Ductile Iron	C1xx Series	B&S, RG, R
Polyethylene	C906	Fused
Steel	C2xx Series	Arc Welded
Molecularly Oriented PVC	C909	B&S, RG, R
Ductile Iron Seismic Joint	C1xx Series	B&S, RG, R
Low to Medium Vulnerability		
Concrete Cylinder	C300, C303	B&S, R
Ductile Iron	C1xx Series	B&S, RG, UR
PVC	C900, C905	B&S, R
Steel	C2xx	B&S, RG, UR
Moderate Vulnerability		
AC > 8" D	C4xx Series	Coupled
Cast Iron > 8" D	None	B&S, RG
PVC	C900, C905	B&S, UR
Concrete Cylinder	C300, C303	B&S, UR
Moderate to High Vulnerability		
AC <= 8" D	C4xx Series	Coupled
Cast Iron <= 8" D	None	B&S, RG
Steel	None	Gas Welded
High Vulnerability		
Cast Iron	None	B&S, Rigid

Utilities can use empirical relationships developed by the American Lifelines Alliance (ALA, 2005) to predict the number of breaks and leaks in your pipeline system. Estimate the time required to both repair the breaks and leaks and restore system functionality based on historical crew productivity data.

*B&S – bell and spigot; RG – rubber gasket; R-restrained; UR – unrestrained
Vulnerability was based on consideration of ruggedness, bending, joint flexibility and joint restraint.
Source: Overview of Piping Systems and their Seismic Vulnerability; Donald Ballantyne, Ballantyne Consulting LLC; National Water and Wastewater Association meeting (2014).

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Standards and Building Codes for Utility Earthquake Resilience

Newly built utility structures should conform to seismic building codes. Existing assets should conform to various standards. The International Building Code (IBC) specifically addresses seismicity in both "design" and "installation" of building systems. Check your local and state building codes.

Title	Code	Standard	Guideline
IBC International Building Code (2015) or applicable jurisdictional building code	X		
ASCE-7, Minimum Design Loads for Buildings and Other Structures (2016)		X	
ALA* Seismic Design and Retrofit of Piping Systems (2002) (primarily above ground pipe)			X
ALA Seismic Fragility Formulations for Water Systems (2001) (used to estimate system pipeline damage)			X
ALA Seismic Guidelines for Water Pipelines (2005)			X
ALA Guidelines for Implementing Performance Assessments of Water Systems (2005)			X
ALA Wastewater System Performance Assessment Guideline (2004)			X
ASCE 41-06 Seismic Rehabilitation of Existing Buildings (2007)		X	
ACI 350-06 Code Requirements for Environmental Engineering Concrete Structures (2006)		X	
AWWA D100-11 Welded Carbon Steel Tanks for Water Storage (2011)		X	
AWWA D110-13 Wire and Strand Wound, Circular, Prestressed Concrete Water Tanks (2013)		X	
AWWA D115-06 Tendon Prestressed Concrete Water Tanks (2006)		X	

*Note: The American Lifelines Alliance (ALA) is no longer in existence, but some of the guidelines they developed are useful for assessing and designing pipelines.

For underground pipelines in water and wastewater systems, there are no earthquake design standards, only guides. Often, the Chief Engineer of a utility is responsible for establishing its design practices and criteria. For example, the San Francisco Public Utilities Commission developed its own internal standard, called General Seismic Requirements for Design of New Facilities and Upgrade of Existing Facilities.

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Additional Earthquake Mitigation Resources

There are many publications and resources for identifying cost effective mitigation measures for earthquakes. These include:

Resource	Description
Recent Earthquakes: Implications for United States Water Utilities	Potential impacts of earthquakes on water utilities and effectiveness of seismic upgrades to tanks, buildings, equipment and pipes. (Water Research Foundation)
Oregon Earthquake Resiliency Plan	Mitigation measures for the anticipated Cascadia Earthquake. Chapter 8 addresses water and wastewater systems. (Oregon Seismic Safety Policy Advisory Commission)
Seismic Guidelines for Water Pipelines	Overview of how to design and install pipelines to mitigate damage from earthquakes. (FEMA, National Institute of Building Sciences, and American Lifelines Alliance)
Earthquake Hazard Mitigation for Utility Lifeline Systems	An overview of strategies for mitigation and response planning for utilities. (FEMA)
Incident Action Checklist - Earthquake	Checklist of activities that water and wastewater utilities can take to prepare for, respond to and recover from earthquakes. (EPA)
Power Resilience Guide	Guide promotes coordination and communication between water sector utilities and their electric utilities; and provides strategies to increase water utilities' resilience to power loss. (EPA)
Water Utilities Fact Sheet	Factsheets of best practices for utilities in earthquake areas. (East Bay Municipal Utilities District)
Is your Water or Wastewater System Prepared? What you need to know about Generators.	An explanation of how to integrate generators into a utility's emergency response operation. Includes an explanation of different types of generators. (EPA)
Seismic Options for New and Old Reservoirs	Presentation of building codes, seismic options and associated costs for water reservoir storage tanks. (Pacific Northwest States AWWA)