Overview of Piping Systems and their Seismic Vulnerability

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Earthquake resistance of pipe is a function of its ability to move with the soil without breaking or pulling apart. This can be achieved by using rugged, ductile materials with restrained or fused/welded joints that can accommodate 1% strain.

Executive Summary

Earthquakes are damaging to buried pipelines. Liquefaction and associated lateral spreading has resulted in the highest damage rates. Cast iron pipe is vulnerable particularly because of its brittle joints, but modern pipelines with unrestrained joints such as ductile iron are vulnerable to joint separation when subjected to permanent ground deformation (PGD).

Wave propagation will damage old brittle pipelines such as those made from cast iron. PGD is of much greater concern for modern pipelines, typically being the hazard that causes the most pipeline failures. In the Pacific Northwest, liquefaction and associated lateral spreading is the most significant contributor to PGD.

Vulnerability varies by the pipe system being used. Brittle pipe systems such as cast iron with leaded joints are the most vulnerable. Pipes that are rugged, resist bending damage, have joint flexibility, and are either continuous or have restrained joints are less vulnerable. Pipelines that combine these characteristics and that can accommodate 1 percent strain are preferred.

Modern pipe systems such as ductile iron and PVC are suitable for installations where moderate levels of wave propagation (ground shaking) are expected. For areas where high levels of wave propagation are expected, continuous or restrained joint pipe should be used. For areas subject to PGD, only pipe that can accommodate 1 percent strain in tension and compression should be used.

Introduction

This paper focuses on practical information that can be used by water system designers to minimize the effect of earthquakes on water distribution systems. Pipe selection is the most important decision to mitigate ground shaking and PGD.

Pipeline vulnerability of systems due to pipeline failure is reviewed considering historic earthquakes. Earthquake hazards are discussed. Pipe systems and their associated vulnerability are developed considering pipe structural parameters and historic pipe performance. Design methods are reviewed and pipeline design guidelines proposed for distribution systems.

The concept of designing pipe to accommodate 1 percent strain is introduced to move with PGD caused by liquefaction and other earthquake hazards. The use of Bionax, molecularly oriented polyvinyl chloride (PVCO) pipe, as well as other pipe systems that meet these 1 percent criteria is discussed.

This document is not intended to address the design of large diameter pipelines, the cost of various pipe systems, or other aspects of the performance of the various pipe systems in the non-seismic environment. The author however realizes that Bionax is a PVC material resistant to corrosion.

Performance in Past Earthquakes

Buried pipelines are vulnerable in earthquakes, having been damaged in every significant event evaluated starting with the San Francisco Earthquake in 1906. Examples discussed here include: Loma Prieta California, 1989; magnitude (M) 7.1, Northridge California, 1994, M6.7; Kobe Japan 1995, M6.8; Christchurch New Zealand 2011, M6.3; and Tohoku Japan 2011, M9.0.

In the 1989 Loma Prieta Earthquake, soils in the San Francisco Marina District liquefied resulting in settlement as shown in Figure 1. Lateral spread was controlled by the seawall separating the area from San Francisco Bay. Approximately 100 cast iron pipes failed rendering the municipal system in the area inoperable (failure locations are shown in Figure 1). The dedicated fire protection system that also served the area was inoperable due to a failure in another location. The San Francisco Fire Department had to rely on water pumped from San Francisco Bay to suppress fires (Ballantyne, 1997).

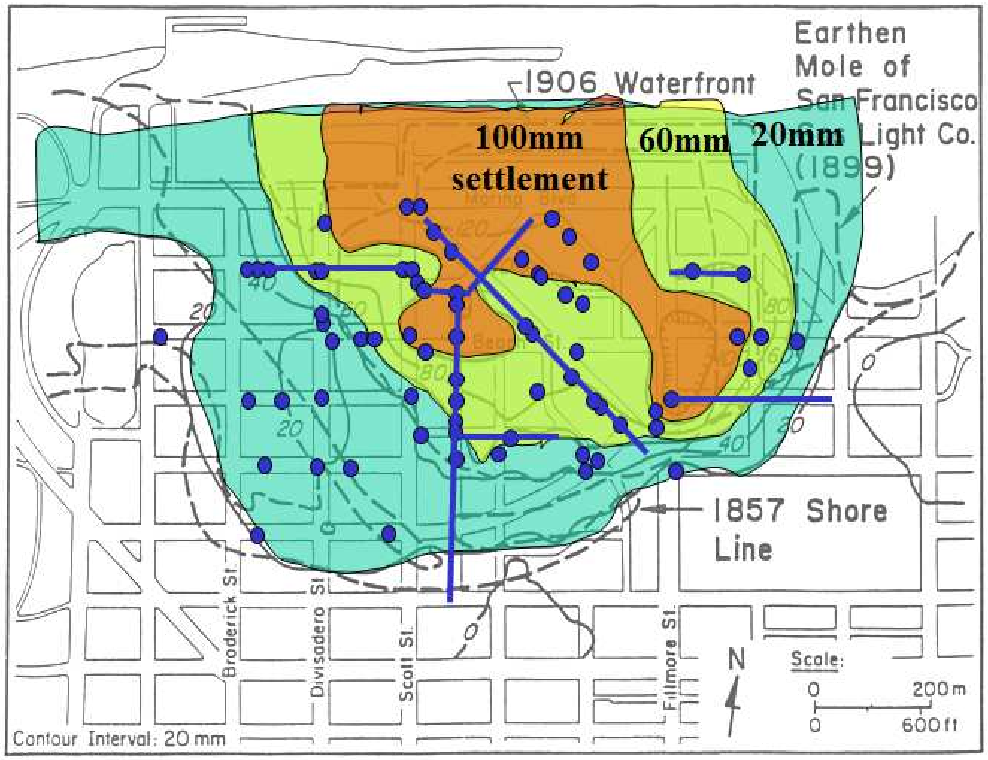

Figure 1. San Francisco Marina District settlement and water main failures in the 1989 Loma Prieta Earthquake (After Professor Thomas O'Rourke)

In the 1994 Northridge Earthquake, the Los Angeles Department of Water and Power's water system suffered approximately 1,000 failures, primariliy in the San Fernado Valley. These failures resulted in two-thirds of the Valley being without water as shown in Figure 2. The Los Angeles Fire Department had to rely on other sources of water such as swimming pools to suppress the 100 ignitions (Ballantyne, 1997).

The 1995 Kobe Earthquake caused 1,200 pipelines to fail within the City which resulted in draining their reservoirs within 6 hours (except those protected by seismic ioslation valves). There was limited water available for fire suppression. Kobe had replaced much of their cast iron pipe with ductile iron pipe in the years prior to the Kobe Earthuake. While the remaining cast iron pipe had a high failure rate, ductile iron pipe pulled joints produced the most failures as shown in Table 1. Photos 1A and 1B show a pulled joint in a crack that opened as a result of liquefaciton/lateral spreading. It took 60 days for Kobe to restore service to 100 percent of their customers as shown in Figure 3 (Ballantyne, 1997).

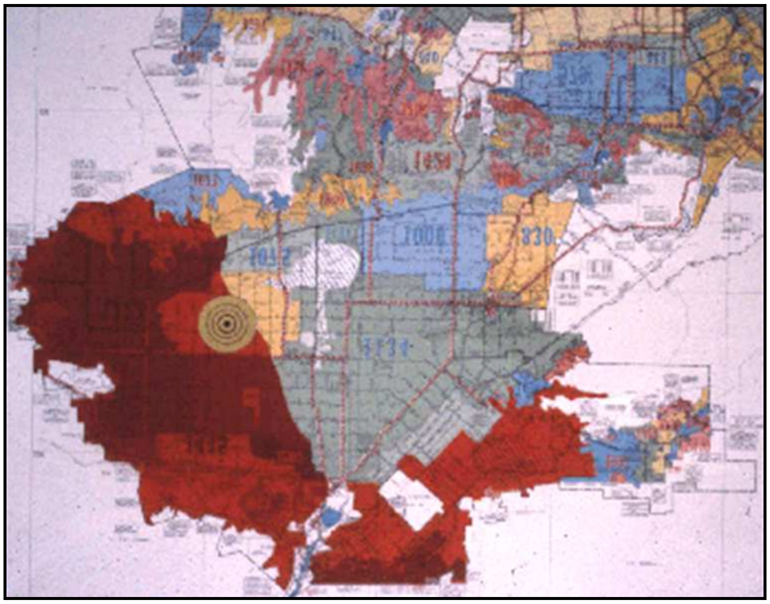

Figure 2. Map of the San Fernando Valley in Los Angeles, the Northridge Earthquake epicenter (tan concentric circles), and the outage area following the event (shaded red).

Table 1. Kobe Water Pipeline Damage Rates

	Failure Rates/km - Number of Failures									
Failure Mode/ Material	**DI (1)**		**CI**		**PVC (2)**		**Steel**		**AC**	
Pipe Length (km)	1874		405		232		30		24	
Barrel	0.00	9	0.63	257	0.38	88	0.34	10	1.24	30
Fitting	0.00	1	0.31	124	0.17	40	0.03	1	0.04	1
Pulled Joint	0.47	880	0.49	199	0.33	76	0.00	0	0.37	9
Joint Failure	0.00	2	0.06	25	0.50	115	0.07	2	0.08	2
Joint Intrusion	0.00	5	0.00	1	0.01	3	0.00	0	0.00	0

Notes:

1. There was no damage to 225 km of ductile iron pipe with seismic joints.
2. Includes PVC pipe with solvent welded joints

Photos 1A and 1B showing ground cracking due to liquefaction/lateral spreading in the vicinity of Osaka Bay, and a pulled joint in a ductile iron pipeline (Kobe 1995).

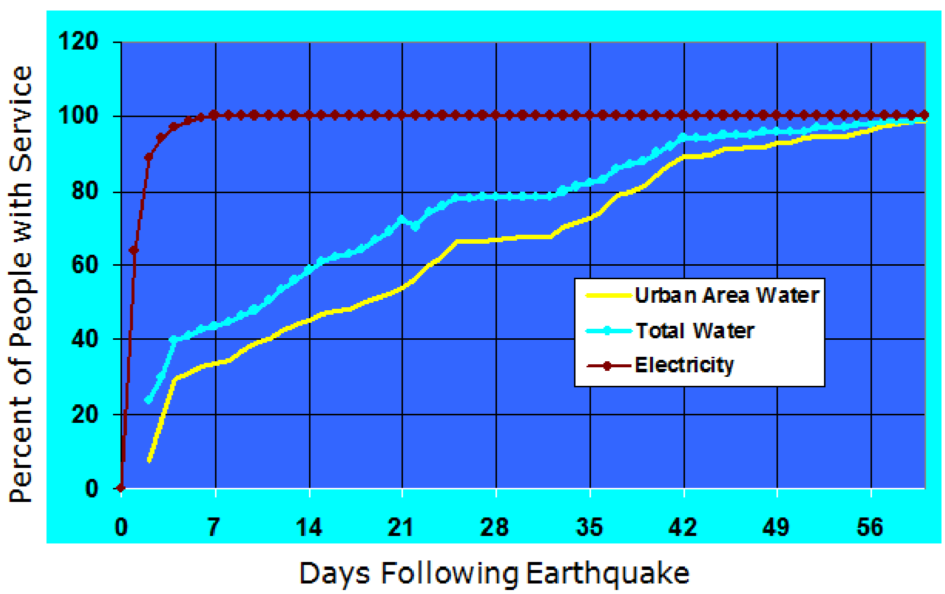

Figure 3. Restoration of the Kobe Electricity, Water Supply in the Urban Area, and Total Water Supply.

Extreme liquefaction along the Avon River in Christchurch in the 2011 earthquake caused 1,645 failures in their 1,600 kilometers of pipe (Figure 4 and Photo 2). It took just

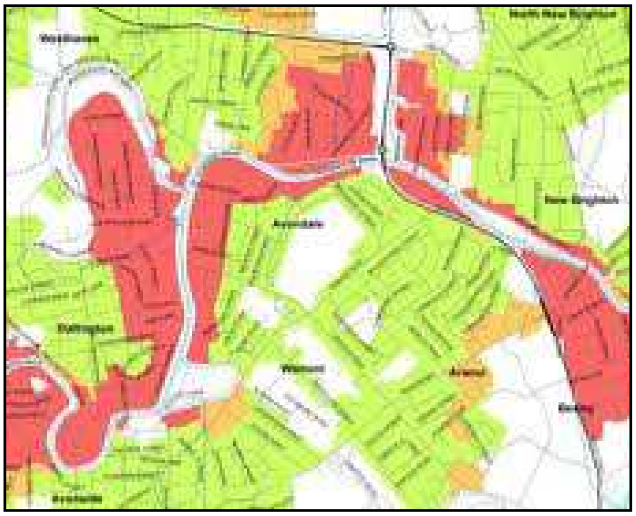

Figure 4. Extreme liquefaction (in red) along the Avon River in Christchurch New Zealand.

Photo 2. Ejected liquefied sand along the Avon River in Christchurch (New Zealand, 2011) (Photo by Tonkin & Taylor)

over 40 days to restore service to areas that were not abandoned. Christchurch had been replacing the original asbestos cement (AC) pipe with PVC, but neither the AC or PVC performed well in the 2011 earthauake, (Eidinger 2012). The PVC pipe failures were due to pulled joints. As a result they moved to the use of high density polyethylene (HDPE) and molecularly oriented polyvinyl chloride pipe as they had much better performance. The advantage of the PVCO pipe was that it could be more readily installed in a wet trench.

The 2011 Tohoku Earthquake impacted water systems primarily along the east coast of Honshu. The large majority of damage covered by the media was from the tsunamis, however, tsunamis damage to buried pipe was limited. Outage times were just over 40 days with the help of mutual aid from other Japanese cities (Eidinger 2012). Reported damage rates ranged from 0.04 failures/km for unrestrained joint DIP to 0.17 failures/km for PVC (including both push-on and solvent-welded joints).

In summary, earthquakes are damaging to buried pipelines. Liquefaction and associated lateral spreading (PGD) has resulted in the highest damage rates. Cast iron pipe is vulnerable particularly because of its brittle joints, but modern pipelines with unrestrained joints such as ductile iron are vulnerable to joint separation when subjected to PGD.

Earthquake Hazards

Pipelines are vulnerable to earthquake wave propagation and permanent ground deformation. Peak ground velocity (PGV) correlates best with wave propagation-related damage. PGV provides a good measure of the differential longitudinal movement along a pipeline. PGV is amplified in (non-liquefiable) soft soils. Wave propagation is damaging to cast iron pipe systems as the brittle leaded joints often fail. Shaking, the most familiar earthquake hazard resulting from wave propagation can also cause hydraulic transients in pipelines.

PGD is typically the most damaging earthquake hazard depending on the extent of unstable soils in the system service area. Failures rates per unit length can be ten times as high as failure rates associated with PGV. PGD can be caused from a number of different hazard phenomena including:

- Surface fault rupture
- Liquefaction and associated lateral spread
- Landslide
- Differential settlement
- Lurching

Surface fault rupture can cause horizontal and/or vertical offsets from a few centimeters to 5 meters or more. Surface faults with moderate return periods are more commonly associated with strike slip faults (e.g. San Andreas Fault in California). They typically have low probabilities of occurrence in the Pacific Northwest.

Liquefaction is one of the most damaging earthquake hazards, particularly for buried pipelines. Liquefaction susceptibility is high in areas with uniformly graded sands that are poorly consolidated, and are below the water table. The deposits must be relatively shallow – less than 10-18 meters deep; at greater depths the overburden pressure limits the likelihood of liquefaction occurring. These conditions are often found in alluvial deposits in river valleys or deltas and in non-engineered fills. Liquefaction probability is a function of susceptibility, shaking intensity and shaking duration. A Peak Ground Acceleration (PGA) shaking intensity threshold of about 15 percent times gravity is typically required to initiate liquefaction.

Liquefaction occurs when poorly consolidated soil particles (Figure 5A) are shaken and realign in a denser configuration (Figure 5B). When this occurs, the water in between the particles is squeezed out raising the pore water pressure, turning the soil into a viscous liquid.

Figure 6 is a map of the British Columbia Lower Mainland showing liquefaction susceptibility. Photo 3 shows an area where liquefaction and lateral spread have occurred.

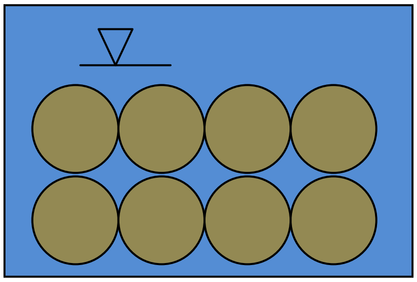

Figure 5A. Poorly consolidated soil particles below the groundwater table.

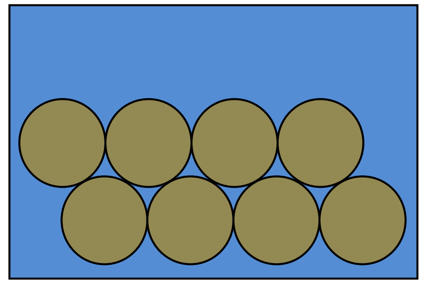

Figure 5B. Soil particles below the groundwater table are consolidated due to shaking. Water is forced out from between the particles and raises the pore water pressure causing liquefaction.

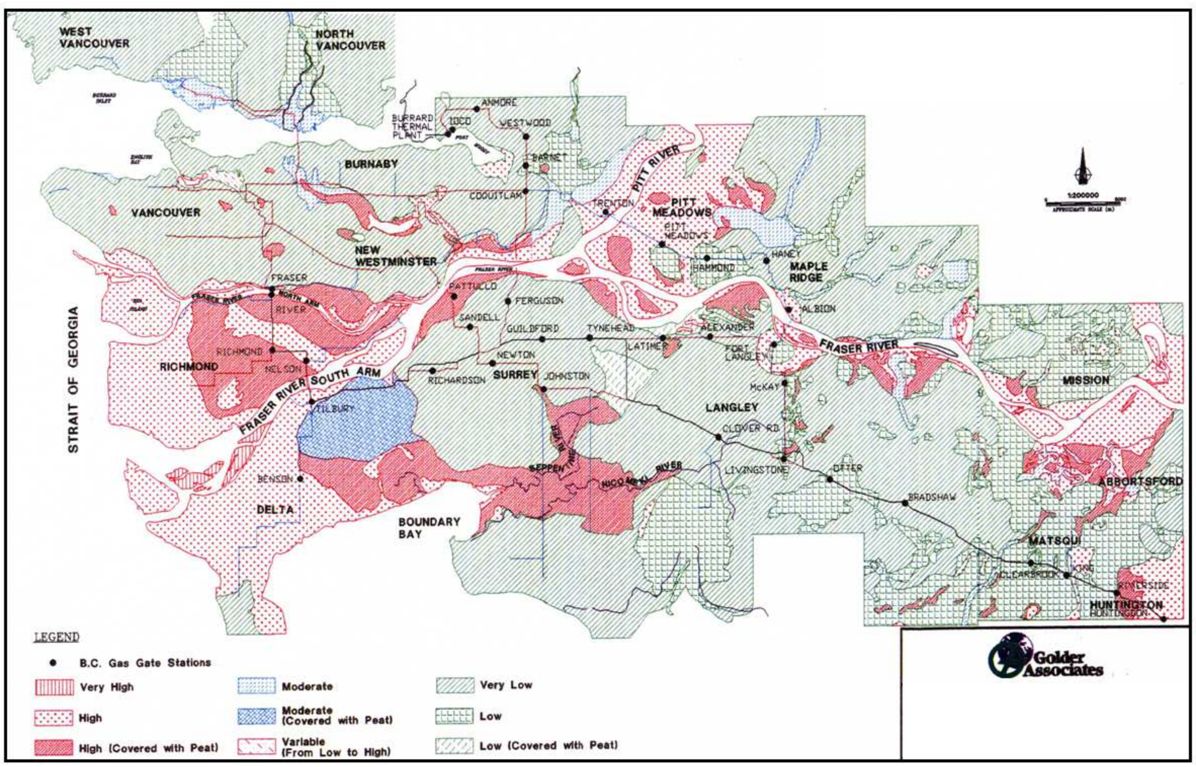

Figure 6. Liquefaction susceptibility map of the Lower Mainland (Map by Golder Associates)

Photo 3. Liquefaction induced lateral spreading (Costa Rica 1991)

When liquefaction occurs, and the topography is sloped, or is near a free face, the liquefied soil will move down gradient. In some instances, it will carry “floating” non-liquefied blocks of soil with it. Pipelines buried in soils that have encountered lateral spreading are likely to fail - see Figures 7 and 8.

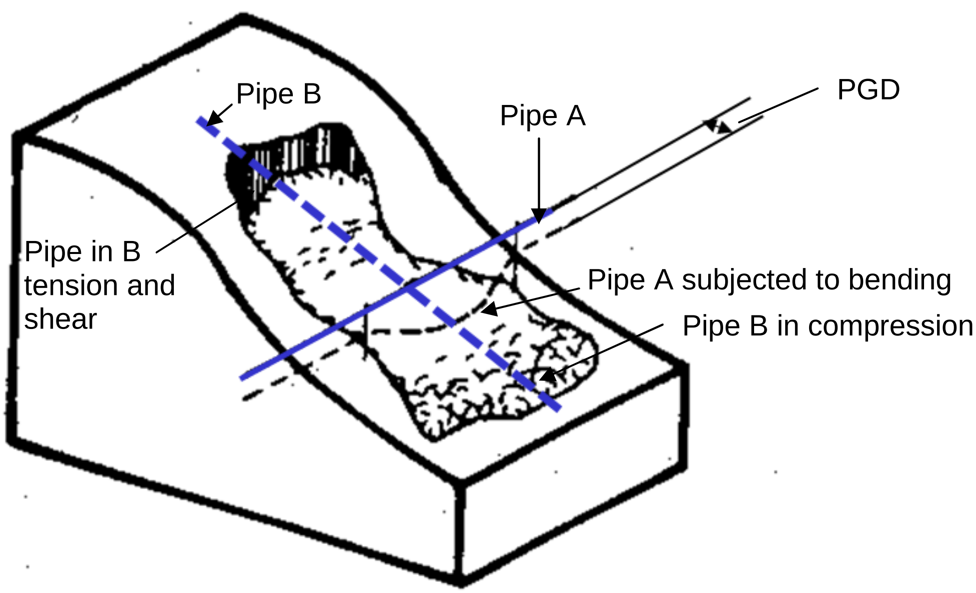

Figure 7. Shows pipes subjected to both transverse lateral spread (Pipe A) which puts in into bending; and lateral spread longitudinal to Pipe B which puts it into tension and shear at the slide scarp, and in compression at the toe of the slide.

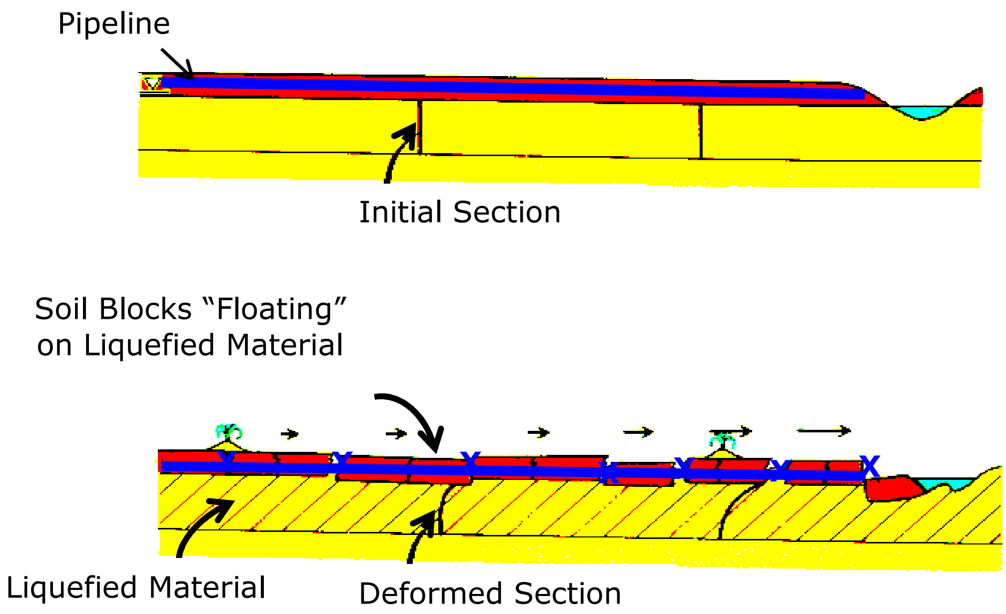

Figure 8. Shows a pipeline adjacent to a river in a deposit that has not been subjected to liquefaction (top); and the section after liquefaction has occurred where the soil blocks (red) are "floating" on the liquefied soil, and are moving towards the river (bottom). Pipe failures would be expected between each block of soil.

PGD, measuring the absolute movement of the soils, is used as a proxy to estimate pipeline damage. The soil strain transferred to the pipe buried in the soil may be a better proxy for pipe damage, but it is more difficult to estimate before an earthquake. One approach to estimate PGD is using the Multiple Linear Regression which relates PGD to a series of parameters including the thickness of the liquefiable layer, the grain size distribution within that layer, the distance from the free face (or the slope), and the height of the free face. The relationship was developed using empirical data from past earthquakes.

Liquefaction susceptibility information is often available from local governments. Liquefaction probability for a particular earthquake, and the resulting PGD, would typically have to be calculated.

Landslide is another form of PGD and can be very damaging to buried pipelines (Photo 4). Landslide PGD deformations can get to be very large. It is very difficult to design a pipeline that can accommodate significant landslide displacements. Landslide hazard mapping is sometimes available from local jurisdictions, but often with less detail than available for liquefaction susceptibility.

Photo 4. Landslide beside a road fill area (Philippines, 1990)

Differential settlement can occur as a result of liquefaction or consolidation in non-liquefiable soils. The most significant problems usually arise at the interface between pile supported structures and pipelines direct buried in soils that settle, and at the interface between undisturbed soil and fill areas.

Lurching is the movement of a block of soil where the ground motion is strong enough to cause failure of a horizontal slide plain under the soil block. These sometimes occur in areas where there is very high intensity shaking. Lurching can sometimes occur as a result of failure of sensitive clay layers such as in Anchorage in the 1964 Alaska earthquake.

In summary, wave propagation measured as a function of PGV will have some impact on old brittle pipe. PGD is of much greater concern, typically being the hazard that causes the most pipeline failures. In the Pacific Northwest, liquefaction and associated lateral spread is the most significant contributor to PGD.

Pipe Vulnerability

Pipe is vulnerable to both wave propagation and PGD. Wave propagation results in differential longitudinal movement usually less than 1 centimeter. As a result, modern bell and spigot pipe systems with elastomeric gaskets can accommodate this level of movement. However, brittle pipe with rigid joints such as cast iron with leaded joints, screwed joint steel, and solvent welded PVC are vulnerable. The pipe barrel and joint are subject to different failure mechanisms. The barrel can fail in compression (wrinkling), extension, shear, bending or blowout. Joints can fail in compression (splitting or telescoping), extension (joint pull out), rotation and shear.

PGD is far more damaging than wave propagation. Large differential movement parallel to the pipe puts it in tension or compression, and movement perpendicular to the pipe puts the pipe in bending or shear. Refer to Figure 7 which shows configurations that would put the pipe in bending, tension or compression. Photo 5 shows ductile iron pipe joints that have failed in compression due to telescoping.

Photo 5. Ductile iron pipe joints that telescoped when they were put in compression. Kobe 1995.

The American Lifelines Alliance developed relationships for the expected number of pipe failures subjected to wave propagation and PGD hazards (G & E Systems, 2001).

For shaking the relationship is:

Repair Rate/1000 feet = K_1 X 0.00187 X PGV

Where K_1 is a constant related to expected performance of different materials

PGV is in cm/sec

For PGD, the relationship is:

Repair rate/1000 feet = K_2 X 1.06 X PGD $^{0.319}$

Where K_2 is a constant related to expected performance of different materials

PGD is in inches

For most pipe materials, K_1 and K_2 are the same. Example values of K are:

Cast Iron – 1
PVC (unrestrained, AWWA-C900) – 0.8
Ductile iron (unrestrained) – 0.5
Steel with welded joints – 0.15

Pipe vulnerability to earthquake shaking and PGD can be related to four parameters (Ballantyne 1995):

- Ruggedness – a function of material strength or ductility to resist shear and compression failures.
- Bending – and function of either beam strength or material ductility to resist barrel bending failures.
- Joint Flexibility – a function of the joint and gasket design to allow elongation, compression, and rotation.
- Joint Restraint – a system that keeps to joints from separating.

Table 2 ranks the relative vulnerability of pipe using these four parameters.

Since the original of Table 2 was developed (Ballantyne 1995), earthquake performance of pipe in Kobe pushed the Japanese to develop design guidelines to mitigate pipe damage due to PGD. Their guidelines (Japan Water Works Association, 1997), to be used in soils that are subject to PGD, require the pipe to be able to withstand 1 percent strain in both tension and compression. This can be accomplished in continuous or restrained joint pipe in two ways, either through pipe ductility or joint movement. Bionax, continuous welded joint or restrained joint steel pipe and fused joint HDPE can meet the standard with the ductility of the pipe. This capability addresses four of the five low vulnerability pipe systems in Table 2.

While restrained joint ductile iron pipe will not pull apart, strain in the pipe induced by PGD in the surrounding soil has to go somewhere. Without relieving the strain it will build up, and the pipe system will ultimately break at the weakest link. The strain in a ductile iron pipe system can be relieved using expansion sleeves at regular intervals to achieve the 1 percent strain relief requirement, which would be required to be competitive with the other pipe systems with Low Vulnerability in Table 2.

Table 2. Relative Earthquake Vulnerability of Water Pipe (after Ballantyne, 1995)

Material Type/Diameter	AWWA Standard	Joint Type	Ruggedness	Bending	Joint Flexibility	Restraint	Total
Low Vulnerability							
Bionax	C909	B&S, RG, R	5	5	5	5	20
Ductile Iron	C1xx Series	B&S, RG, R	5	5	4	4	18
Kubota Seismic Joint Ductile Iron	NA	Special	5	5	5	5	20
Polyethylene	C906	Fused	4	5	5	5	19
Steel	C2xx Series	Arc Welded	5	5	4	5	19
Steel	C2xx Series	B&S, RG, R	5	5	4	4	18
Low/Moderate Vulnerability							
Concrete Cylinder	C300, C303	B&S, R	3	4	4	3	14
Ductile Iron	C1XX Series	B&S, RG, UR	5	5	4	1	15
PVC	C900, C905	B&S, R	3	3	4	3	13
Steel	C2xx	B&S, RG, UR	5	5	4	1	15
Moderate Vulnerability							
AC > 8" D	C4xx Series	Coupled	2	4	5	1	12
Cast Iron > 8" D	None	B&S, RG	2	4	4	1	11
PVC	C900, C905	B&S, UR	3	3	4	1	11
Concrete Cylinder	C300, C303	B&S, UR	3	4	4	1	12
Moderate/High Vulnerability							
AC <=8" D	C4xx Series	Coupled	2	1	5	1	9
Cast Iron <= 8" D	None	B&S, RG	2	1	4	1	8
Steel	None	Gas Welded	3	3	1	2	9
High Vulnerability							
Cast Iron	None	B&S, Rigid	2	2	1	1	6

B&S-bell & spigot; RG-rubber gasket; R-restrained; UR-unrestrained

The Japanese ductile iron pipe industry has developed a joint with built in joint strain relief. The Kubota seismic joint allows 1 percent movement in compression or tension, and then hits a stop. The displacement is then transferred to the adjoining pipe which is pushed or pulled through the ground, transferring the needed strain relief to the next joint.

Bionax pipe is stronger and more ductile than traditional AWWA C900 PVC pipe. The brittle nature of PVC is why it is considered to have a Low/Moderate Vulnerability in Table 2. Bionax can meet the 1 percent strain criteria in three ways. First, the pipe is ductile; the material has the capability to stretch up to 5 percent in tension, and the Bionax with the restrained joint tested could handle 1.7 percent strain before the joint restraint broke the pipe. Second, in compression the pipe joints can telescope without breaking the bell or the hydraulic seal. Third, the bell depth allows several inches of extension before the hydraulic seal is broken, so the joint harness used on the pipe can be installed to allow that several inches of movement before the nuts are engaged on the harness bolts.

In summary, pipe is vulnerable to both wave propagation and PGD, with PGD resulting in much higher rates. Vulnerability varies by the pipe system being used. Brittle pipe systems such as cast iron with leaded joints are the most vulnerable. Pipes that are rugged, resist bending damage, have joint flexibility, and are either continuous or have restrained joints are less vulnerable. Pipelines that combine these characteristics and accommodate 1 percent strain are preferred.

Pipe Recommendations for Earthquake

There are no seismic resistant pipeline standards in the water industry in North America. The author has recommended the design practices described below to utility clients. Three hazard conditions are considered:

Wave Propagation – Peak Ground Acceleration < 40% x Gravity

This condition exists where there are non-liquefiable soils, and otherwise not subject to PGD. 40% PGA is considered a moderate level of shaking intensity. Refer to the local government jurisdiction for PGA design criteria.

For this condition, commonly used pipe materials such as non-restrained joint ductile iron or PVC are acceptable. Modern bell and spigot joints with elastomeric gaskets are adequate to accommodate pipe strain induced by wave passage.

Wave Propagation - Peak Ground Acceleration 40% x Gravity or Greater

This condition exists where there are non-liquefiable soils, and otherwise not subject to PGD. There is potential for joint separation to occur particularly in soft soils where ground motions are amplified. Pipe systems with a deeper bell depth will perform better.

For this condition, welded steel, restrained joint ductile iron, restrained joint Bionax, or HDPE pipe is recommended.

PVC (C-900) is not recommended for this application. PVC is more brittle than more ductile piping material such as Bionax or ductile iron. The PVC pipe bell-spigot assembly is designed like a wedge, and can split the bell when subjected to compression. However, one purveyor had good success with PVC in the Northridge Earthquake, possibly because of it deep bell depth. There has only been limited exposure of PVC pipe to earthquakes, so there is a limited empirical data base on which to judge its performance. Most of the PVC pipe exposed in the Kobe Earthquake was small diameter, typically less than 75 to 100 mm and likely used solvent welded joints so it had no longitudinal flexibility.

Permanent Ground Deformation > 5 cm

The PGD condition exists anywhere there are liquefiable soils, areas landslides, and locations in fault zones.

For this condition, welded steel, restrained joint ductile iron with expansion sleeves or joints, restrained joint Bionax, or HDPE pipe is recommended. Use of these pipe materials will enhance seismic performance, but may not provide absolute assurance that the pipe will not fail.

In addition to use of these materials, the following items should be considered:

- Relocate the pipe to a different corridor
- Install below liquefiable layer
    - Directional drilling or micro tunneling
    - Useful for river crossings
- Improve the soils to reduce liquefaction/lateral spread
    - This is very expensive and is probably limited to very critical, and/or large diameter pipe
    - Soil mitigation can include: installation of gravel columns or soil grouting
- Support the pipe on piles (designed for lateral spread loads)
    - This is very expensive and is probably limited to very critical, and/or large diameter pipe
- Design the pipe to move, e.g., pulling it through the soil
    - Design layout to put pipe in tension
    - Minimize anchors to allow the pipe to slide through the ground to distribute the strain
    - Provide flexibility at connections to structures or other hard points
    - Use light backfill to allow the pipe to slide
    - Wrap metallic pipe in polyethylene – reduce soil/pipe friction

In summary, current commonly used pipe systems are all suitable for installations where moderate levels of wave propagation are expected. For high levels of wave propagation are expected, continuous or restrained joint pipe should be used. For areas subject to

PGD, only pipe that can accommodate 1 percent strain in tension and compression should be used.

Conclusion

Earthquake hazards, particularly PGD, damage pipelines. Pipes that are rugged, resist bending damage, have joint flexibility, and are either continuous or have restrained joints are less vulnerable. Pipelines that combine these characteristics and that can accommodate 1 percent strain are preferred in areas subject to PGD. Pipe systems that meet these stringent criteria include: Bionax with restrained joints, Kubota ductile iron pipe with seismic joints, steel with welded or restrained joints, fused joint HDPE, and restrained joint ductile iron with special provisions to accommodate expansion and compression. Bionax and HDPE are made with plastics making them good choices in corrosive environments.

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