RELATIVE EARTHQUAKE VULNERABILITY OF WATER PIPE

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ABSTRACT

This paper discusses the basis for the relative earthquake vulnerability of water pipeline systems as presented in the recent American Water Works Association publication, *Minimizing Earthquake Damage, A Guide for Water Utilities* by Donald Ballantyne, as summarized in Table 1. The paper is important and timely considering the Northridge and Kobe earthquakes. The paper provides a more in-depth background of pipeline failure modes than provided in the AWWA publication.

Pipeline systems include those for which AWWA has a current standard, and older pipeline systems that have large installed inventories in the United States.

Earthquake pipeline damage mechanisms are described, and the ability of each pipeline system to resist those damage mechanisms is discussed. The pipeline vulnerability is related to pipe material and joint type as listed in Table 1.

Pipeline systems are suggested for use in different geologic settings. The paper also suggests improvements that might be made to piping systems to improve their earthquake performance.

INTRODUCTION

Pipeline failure in earthquakes has lead to failure of systems to provide water for fire protection and drinking in the 1995 Kobe, Japan; 1994 Northridge and 1989 Loma Prieta, California earthquakes. Proper selection of pipe materials for new installations and replacement of vulnerable pipe segments critical to operation is important. In addition, there may be opportunities to improve existing pipe designs to make them more earthquake resistant.

The objective of this paper is to describe a method to rate the earthquake vulnerability of buried water pipe to earthquake induced permanent ground deformation, PGD. The system can be used to:

1. Select appropriate pipe for new installations
2. Prioritize pipe within a water system to be replaced
3. Provide direction in developing an earthquake resistant pipe design.

Earthquake wave passage damage rates for pipe types currently being installed are approximately one order of magnitude less than for PGD damage rates.
While wave passage damage can be significant in total numbers, it is usually widely distributed throughout the system, and mitigation is difficult, and will not be considered in this paper.

The piping systems discussed in this paper are buried installations of pipe commonly used for transmission and distribution in the water supply industry. Service line piping system are not discussed.

In developing the method, it has been assumed that pipelines move with the ground. PGD is the primary hazard causing pipeline earthquake damage. Pipelines can be designed to be more resistant to PGD.

**PIPE MATERIAL AND JOINT TYPES**

Materials commonly used for potable water transmission and distribution pipe include ductile iron, steel, concrete cylinder, and polyvinyl chloride, PVC. Polyethylene has only recently been approved as an AWWA standard, and is becoming a more accepted pipe material. Asbestos cement has been used extensively in the past, but sees minimal use for new installation. In the early 1970's, ductile iron replaced cast iron for new installations.

Pipe joints commonly used for potable water pipelines include bell and spigot, B&S, with elastomeric gasketed joints (Figure 1), or welded joints (Figure 2). Asbestos cement pipe is joined with couplings that work like a double bell, back-to-back. Steel and polyethylene can employ butt joints that are welded (steel pipe) or fused (polyethylene pipe) together. Older steel pipe barrels and joints were sometimes riveted. Until the 1950's, cast iron pipe joints were commonly sealed with lead or mortar, making them rigid.

When conducting an evaluation of an existing pipeline system, the pipe type and joint type can sometimes be identified by knowing the date of installation.

There are many variations on the pipe and joints described above.

**JOINT RESTRAINT**

Joint restraint is an important parameter to evaluate earthquake vulnerability.

Bell and spigot pipe joints and coupled (asbestos cement) pipe do not provide joint restraint unless special hardware is added.

Both bolted (Figure 3) and boltless (Figure 4) restrained joint designs have been developed to be an integral part of the joint design (Figure 3). Restained joint systems available in the United States offer only minimal longitudinal deformation once the joint is installed. This means that any longitudinal movement from the PGD
in the surrounding soil along the pipe must be dissipated in pipe strain. This may put very large longitudinal loads on pipe joints causing them to fail.

The Japanese have developed the “S” and “SI” restrained joint that allows some longitudinal movement, to a point, when the retainer ring stops pull out (Figure 5). With this design, when longitudinal deformation is initiated, it will be taken up in the first joint. If the first joint does not have the extension capacity, it is passed along to the second joint, and so on, similar to the way railroad train car connections take up slack when the train starts. Strain buildup is minimized which then controls longitudinal loading across pipe joints.

Welded steel and fused polyethylene joints are inherently restrained.

EARTHQUAKE HAZARDS

Earthquake hazards are the ground movement mechanisms associated with earthquakes. They include movement from earthquake wave propagation, as well as PGD.

Wave Passage

Propagating earthquake waves move the soil as they pass. The soil moves back to its original position once the wave has moved on. Waves can be in the form of either sine waves or compression waves. Sine waves move the pipe laterally. Most pipe can readily accommodate some lateral movement. Compression waves cause differential longitudinal movement along the pipe axis. Most pipe systems currently in use, such as concrete cylinder pipe (Figure 6), can accommodate some differential movement from wave passage by either accommodating it in the joint, or in pipe strain and ductility. Some damage from wave passage may occur, but it will be widely distributed throughout the system. If the length of pipe subjected to wave passage is much larger than that subjected to PGD, the total numbers of pipe failures from the two hazard may be comparable. Brittle pipe with rigid joints are subject to significant damage from wave passage.

Permanent Ground Deformation

PGD can be caused by liquefaction, lateral spread, settlement, lurching, landslides, and fault rupture. It can put tension, compression, bending, and shear loads on pipelines.

PGD can occur as a result of liquefaction caused lateral spread when the soil moves down a slope (a 2 percent slope is sometimes considered a threshold) or towards a free face. Liquefaction is caused by ground shaking that consolidates soils particles, forcing out water from between the particles. As the water tries to escape,
it turns the soils into a quick condition. Liquefaction can also result in loss of bearing capacity or flotation of buried pipes. Significant flotation usually is limited to sewers that are not filled with liquid, making them more buoyant.

Settlement occurs when soil consolidation takes place, but there is no water present. Lurching occurs when soil masses are thrown by earthquake ground motion, and do not return to their original location.

Landslides move down slope in magnitudes ranging from millimeters when creep occurs, to tens and hundreds of meters when flow slides occur.

Fault rupture moves soil on one side of the fault relative to the ground on the other side of the fault.

**Geographic Information Systems for Hazards Mapping**

One opportunity to mitigate earthquake damage is to avoid areas where PGD is expected, or to modify soils to mitigate the PGD. A Geographic Information System, GIS, is an excellent tool to map hazards, and then overlay pipe material and joint type vulnerabilities to those hazards. The resulting map can be a useful tool for 1) planning of pipeline alignments, 2) use as a design guide to direct pipe material selection, 3) conducting vulnerability assessments, and 4) can also be employed for emergency response and restoration.

**PIPE PERFORMANCE PARAMETERS**

Four pipeline performance parameters have been identified in an attempt to rate the earthquake vulnerability of pipelines. These parameters were selected based on pipe material and joint type, and their respective earthquake damage mechanisms. The pipeline performance parameters are:

1. **Ruggedness**
2. **Resistance to Bending Failure**
3. **Joint Flexibility**
4. **Joint Restraint**

Ruggedness is a function of pipe material strength and ductility. It is a factor in pipe failure in compression, shear, bursting, and to a lesser degree, tension and bending.

Resistance to bending failure of the pipe barrel (or body) is a function of the pipe barrel’s strength in bending. Non-ductile pipe such as cast iron and asbestos cement, 8-inch and smaller are particularly vulnerable in this category. Cast iron
pipe may be slightly stronger, but the nominal laying lengths are half again as long as for asbestos cement pipe, allowing for a longer moment arm to cause bending failure. Large diameter, non-ductile pipe typically has adequate strength to resist failure in bending. Alternatively, if the pipe barrel will bend while stressing the pipe material beyond its yield point, if the pipe bends ductily without breaking, it is considered to be resistant to bending failure.

Joint flexibility is a function of a pipe's ability to extend, compress, or bend (or rotate) around the joint without breaking the joint's water-tight seal.

Joint restraint is a function of the pipe-joint system to hold together in extension.

A fifth parameter, condition, should be considered for existing pipe. Pipe that has corroded, as identified by soil corrosivity, field inspection, or poor maintenance history, will likely perform worse than similar pipe in good condition.

PIPE DAMAGE MECHANISMS

Pipe earthquake damage mechanisms are important to consider when rating earthquake vulnerability. Damage mechanisms can be segregated into two groups, pipe joint, and pipe barrel, and are listed below. The pipe performance parameter that is most significant in controlling the respective mechanism is listed following each, separated by a dash.

Pipe joints usually fail in the following ways:

- Extension (pulled joints) - joint restraint (Figure 7)
- Compression (split joints) - ruggedness (Figure 7)
- Bending/Rotation - joint flexibility and ruggedness (Figure 8)

In the Kobe Earthquake, approximately two-thirds of the pipe failures were from joint extension or compression. One reason that other types of failures were minimized in Kobe is that 89 percent of the pipe was either ductile iron or welded steel.

Pipe barrels usually fail in the following ways:

- Shear - ruggedness (Figure 9)
- Bending - resistance to bending failure and ruggedness (Figure 8)
- Hole (condition)
• Split/Burst - ruggedness and condition

Holes are usually a result of corrosion. Split of burst pipes can be the result of corrosion, often combined with water hammer. Pipes can collapse; usually this is limited to failure of non-pressure pipelines that have a weaker cross section.

Pipe failures are often associated with bends and fittings, hydrant connections, service connections, and valves where there is a discontinuity in the pipeline.

WELDED STEEL PIPE JOINTS

Pipe joint welding should be further examined to differentiate vulnerability associated with a range of issues including gas versus arc welding, lap versus butt joints, and bell design.

In both the 1971 San Fernando and 1994 Northridge earthquakes, gas welded steel pipe performed much worse than arc welded steel pipe. Typically, the gas welded steel pipe was installed before 1940. Two considerations have been raised that may lead to its poor performance, 1) quality control, particularly of weld penetration, and 2) embrittlement of pipe material properties adjacent to the weld.

Welded lap joint allow some eccentric loading in the joint as compared to butt welded joints that have no eccentric loads. To some degree, this can be controlled by providing equal welding on both the inside and outside of the joint. Interior welding is limited by pipe diameter.

It has been suggested that the bell manufacturing process, material properties of the metal are changed when the bell is formed. This concern may be limited to larger diameter pipelines as a result of the limitation of the manufacturing equipment. The radius of the bend at the back of the bell may also influence pipe bell load transfer characteristics.

Therefore, gas welded pipe joints are rated much lower than arc welded joints. Although not shown in Table 1, pipe with butt welded joints should be rated less vulnerable than pipe with lap welded joints.

PIPE MATERIAL AND JOINT TYPE RATING

Based on observations of pipeline performance in recent earthquakes, pipe material and pipe joint types were rated for ruggedness, resistance to bending failure, joint flexibility, and joint restraint. The results are shown in Figures 10 through 13, respectively. The ratings for each parameter are summed to get a net vulnerability. Consideration was given to weighting one performance parameter higher than others. Further evaluation comparing earthquake performance and vulnerability rating indicated even weighting seemed appropriate. The results are summarized in Table
1. It should be noted that there have been slight modifications to the pipe vulnerability ratings compared to those included in the original AWWA publication.

The results in Figure 10, Ruggedness, show that pipe manufactured from asbestos cement and cast iron have a moderate to high vulnerability. Concrete cylinder pipe, a composite of steel and concrete, PVC, and gas welded steel are considered to be moderately rugged.

The results in Figure 11, Resistance to Bending Failure, show that asbestos cement and cast iron pipe 8-inch and smaller is particularly vulnerable to bending. The rigid joint cast iron pipe includes all pipe diameters, so does not have as low a rating.

The results in Figure 12, Joint Flexibility, show that gas welded and rigid bell and spigot pipe are particularly vulnerable to joint movement.

The results in Figure 13, Joint Restraint, show that all unrestrained joint pipe is vulnerable to extension (pull apart) failures. Restrained joint concrete cylinder pipe and PVC are downgraded because the pipe barrel and restrainer attachments are not as strong as for steel and ductile iron pipe.

An additional level, very low vulnerability, is proposed. It would include butt welded steel, and ductile iron pipe with the Japanese “S”, and “SII” joint. Butt welded steel joints are stronger than bell and spigot welded steel joints. S joint ductile iron pipe is designed to minimize strain buildup by providing some longitudinal extension before it restraints further movement.

PIPELINE LININGS AND COATINGS

Pipelines have been evaluated on the merits of their basic material. In some cases, mortar and/or cement linings and coatings are added to pipelines to resist corrosion. These materials are less ductile than steel or concrete. In the case of mortar lined and coated ductile iron or steel pipe, the coating may have tendency to limit the ductile performance of the pipe. If the pipe loading forces the pipe to deform significantly, the mortar may spall, allowing corrosion to begin.

PIPELINE FITTINGS AND APPURTECNANCES

A pipeline system is only as strong as its weakest component. Therefore, fittings and appurtenances such as valves and hydrants should be constructed on rugged materials. Air release valves should be designed to accommodate water hammer. Service connections should be designed to accommodate differential movement.
CONCLUSIONS AND RECOMMENDATIONS

Pipelines are vulnerable to PGD. To mitigate earthquake damage there are several strategies listed below.

For new pipe:

- Avoid high earthquake hazard areas. Use GIS as a tool to assist in mapping hazards.
- Use low vulnerability pipe in high hazard areas.
- Design appurtenances and connections to be equally earthquake resistance.

For existing pipe:

- Upgrade vulnerable critical pipeline segments.
- Implement a prioritized replacement program.

For all pipeline systems:

- Install operational flexibility.
- Build in emergency response capability.

REFERENCES

1. American Water Works Association - Pipe Standards, See Table 1, Denver CO.


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B&S - bell & spigot; RG - rubber gasket; R - restrained; UR - unrestrained
Figure 1
Tyton Type Bell and Spigot Joint

Figure 2
From Top to Bottom, Lap-Welded Slip, Single-Butt Weld, and Carnegie-Shape Rubber Gaskets Joints

Figure 3
Bolted Restrained Push-on Joint
Figure 4
Boltless Restrained Joints

*S* Joint (500 - 2600 mm Diameter)

Figure 5
Seismic Joints (S ans SII)

Figure 6
Concrete Cylinder Pipe Joint
Figure 7
Extension (top) and Compression (bottom) Failures

Figure 8
Bending

Figure 9
Shear
Figure 10
Pipe Material Ruggedness

Figure 11
Pipe Material Resistance to Bending
Figure 12
Joint Flexibility

Figure 13
Joint Restraint