Pipelines – Seismic Vulnerability Assessment of Water Systems

Don Ballantyne
MMI Engineering
Federal Way, Washington

Pacific Northwest Section
American Water Works Association
May 2, 2008

Overview

- Earthquake Hazards
- Damage Mechanisms
- Pipe Types & Performance
- Loss Estimation
- Pipeline Design and Mitigation
- Conclusions and Recommendations

Earthquake resistance of pipe is a function of its ability to move with the ground without breaking.

(Even very strong pipe that is brittle is hardly ever strong enough to resist ground movement, and so, it will break.)

Earthquake Hazards

- Wave Propagation (Ground Motion)
  - Peak Ground Velocity
- Permanent Ground Deformation (PGD) - 10X damage
  - Fault Rupture - displacement
  - Liquefaction/Lateral Spread – displacement (Bartlett & Youd)
  - Landslide – displacement
  - Differential settlement
  - Lurching
- Hydraulic Transients

Wave Propagation Ground Strain and Curvature

- Seismic wave propagation induces ground strains (problem) and curvature (not a problem)
- Maximum ground strain (Newmark, 1967)

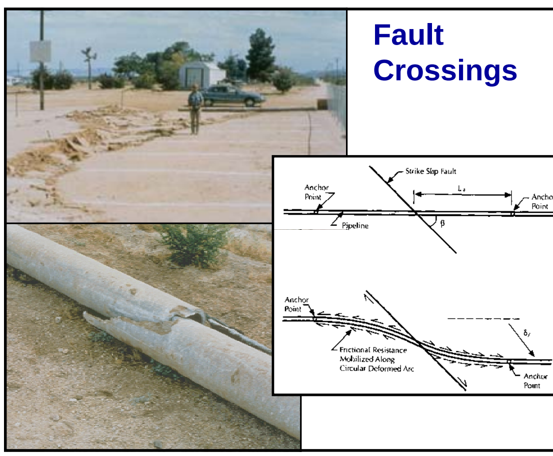
$$\varepsilon_g = V_m / C$$

V_m= max. horiz. ground velocity in the direction of wave propagation - function of ground motion intensity

C = wave propagation velocity, a function of the soil – rock fast (large number), soft soils – slow (small number)

- Usually only a problem on pipe with brittle joints such as lead joint CIP.
- Modern pipe with gasketed joints performs well except in extreme earthquakes

Fault Crossings

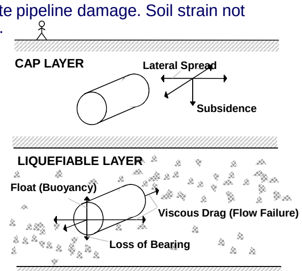


Liquefaction

Pipeline and Manholes Float in Liquefiable Soils

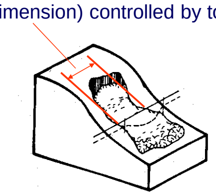
Liquefaction/Lateral Spread

- PGD used as a proxy to estimate pipeline damage. Soil strain not evenly distributed along ground.
- PGD is proportional to shaking duration, so the larger the magnitude, the greater the PGD
- Typically use Multiple Linear Regression analysis to estimate PGD, based on empirical data (Bartlet & Youd).
- Pipe may be in non-liquefiable cap layer or within liquefiable layer.



Liquefaction/Lateral Spread – cont.

- For detailed assessments, Newmark sliding block and/or finite element analyses are used.
- For continuous pipe, size of block that moves is most important. (similar to development length for rebar) Block size (dimension) controlled by topography.



Continuous Pipe Design Parameters in Liquefiable Soils

Demand

Liquefaction/Lateral Spread/Landslide
- Block size
- Permanent Ground Displacement (PGD)

Geotechnical
- Depth of burial/type of backfill
- Soil-pipe coefficient of friction (use polyethylene encasement)

Layout
- Unanchored length

Capacity

Pipe/Material Selection
- Structural/material parameters - strength, allowable strain, ductility
- Wall thickness/Diameter
- Joint/Weld

Earthquake Hazard Determination

- Liquefaction susceptibility
  - Hazard mapping (DOGAMI, DNR, USGS)
  - Geologic mapping - alluvial deposits, fills
  - Groundwater table < 15m deep
  - Simplified Methods (Seed-Idriss)
- Lateral spread - multiple linear regression (MLR) analysis (Youd)
- Landslide - geologic mapping

Pipeline Damage Mechanisms

- Barrel
  - Compression
  - Extension
  - Shear
  - Bending
  - Burst/Blowout
- Joint
  - Compression
  - Extension/Pull Out
  - Rotation
  - Shear

Compression Displacements

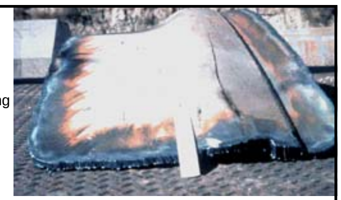
- Pipe barrel compression failure
- Joint compression failure

Tension Displacements

- Joint pull out (provide restraint)
- Strain release
  - Pipe material ductility
  - Joint flexibility (Japanese "S" joint)

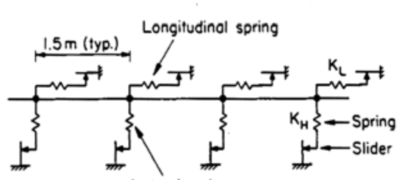
Steel Pipe

- Welded joint failure
  - Steel weakened by strain hardening, heating during welding
  - Bending moment across bell & spigot lap joint
  - Stress concentration at double wall section
- Barrel compression failure
- Cement coating reduces ductility; mortar lining may spall
- Joint design
  - Butt welded – 100% barrel strength
  - B&S - split weld in AND out ~ 2/3 barrel strength
  - B&S - split weld in OR out ~ 1/3 barrel strength
  - Gasketed B&S – deep socket



Continuous Pipe Analysis

Spring/slider parameters between pipe/soil used for detailed analyses

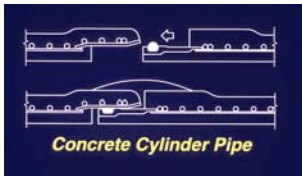


Anchors

- Bends, tees, service connections, valves/vaults
- No anchors - pipe allowed to slip through ground up to several thousand feet
- Anchors - result in stress concentrations

Concrete Cylinder Pipe

- Reinforcement designed for hoop stresses
  - Dependent on can to carry tensile/ compressive loading
- Weak connection to "Can"



PVC versus Ductile Iron Pipe

- Joint depth - pull out
- Joint rotation capacity
- Wedge effect
- Material strength and ductility


Philippines, 1990

Corrosion-Related Failures

House Services

- 10,000+ failures in Kobe, 8x distribution system failures
- Large numbers result in significant hydraulic impact
- PE and copper perform well.
- Rigid joints pipe such as threaded steel and solvent welded PVC are vulnerable.

Pipe Appurtenances

- Use ductile materials
- Avoid brittle materials


Water Hammer
Northridge, 1994


Water Hammer
Northridge, 1994


Compression Failure
San Fernando, 1971

Pipe Characteristics Affecting Seismic Performance

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

Material Type/Diameter	AWWA Standard	Joint Type	Rugged-ness	Bending	Joint Flexibility	Joint Restraint	Total (out of 20)
Low Vulnerability							
Ductile Iron	C1xx Series	B&S, RG, R	5	5	4	4	18
Polyethylene	C906	Fused	4	5	5	5	19
Steel	C2xx Series	Arc Welded	5	5	4	5	19
Steel	None	Riveted	5	5	4	4	18
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

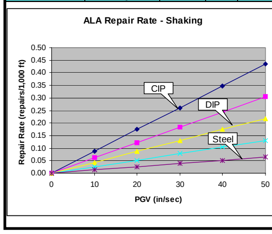
B&S - bell & spigot; RG - rubber gasket; R - restrained; UR - unrestrained

GOOD

Relative Earthquake Vulnerability of Water Pipe

BAD

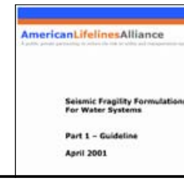
Pipe Material	Joint Type	Soils	Diam	K_1
Cast iron	Cement	All	Small	1.0
Cast iron	Cement	Corrosive	Small	1.4
Cast iron	Cement	Non corr.	Small	0.7
Cast iron	Rubber gasket	All	Small	0.8
Welded steel	Lap-Arc welded	All	Small	0.6
Welded steel	Lap-Arc welded	Corrosive	Small	0.9
Welded steel	Lap-Arc welded	Non corr.	Small	0.3
Welded steel	Lap-Arc welded	All	Large	0.15
Welded steel	Rubber gasket	All	Small	0.7
Welded steel	Screwed	All	Small	1.3
Welded steel	Riveted	All	Small	1.3
Asbestos cement	Rubber gasket	All	Small	0.5
Asbestos cement	Cement	All	Small	1.0
Concrete w/Stl Cyl	Lap-Arc Welded	All	Large	0.7
Concrete w/Stl Cyl	Cement	All	Large	1.0
Concrete w/Stl Cyl	Rubber gasket	All	Large	0.8
PVC	Rubber gasket	All	Small	0.5
Ductile iron	Rubber gasket	All	Small	0.5



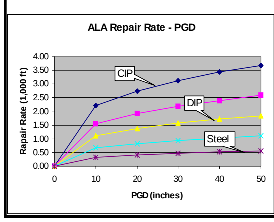
ALA Damage Relationships - Shaking

Repair Rate/1000 feet = K_1 * (0.00187)* PGV

Repairs taken as 20% breaks and 80% leaks for wave propagation



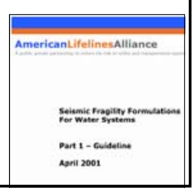
Pipe Material	Joint Type	K_2
Cast iron	Cement	1
Cast iron	Rubber gasket	0.8
Cast iron	Mechanical restrained	0.7
Welded steel	Arc welded (large diameter, non corrosive)	0.15
Welded steel	Rubber gasket	0.7
Asbestos cement	Rubber gasket	0.8
Asbestos cement	Cement	1
Concrete w/Stl Cyl	Welded	0.6
Concrete w/Stl Cyl	Cement	1
Concrete w/Stl Cyl	Rubber gasket	0.7
PVC	Rubber gasket	0.8
Ductile iron	Rubber gasket	0.5



ALA Damage Relationships - PGD

Repair Rate/1000 feet = K_2* (1.06) * $PGD^{0.319}$

Repairs taken as 80% breaks and 20% leaks for PGD



Loss Estimation Methodology

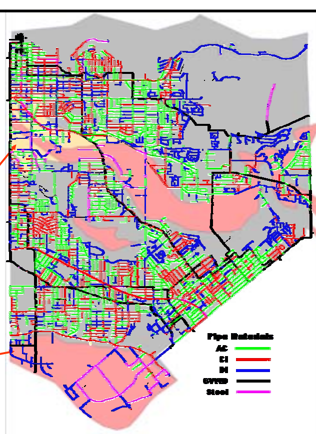
- Hazards
  - Shaking - intensity
  - Liquefaction - susceptibility, displacement
- Pipe type
  - Material
  - Joint type
  - Diameter
  - Condition
- Estimate losses by applying damage relationships
- Output in GIS, database, and/or spreadsheet format

MMI

Burnaby, BC Geologic Hazard Overlaid by Pipe Material

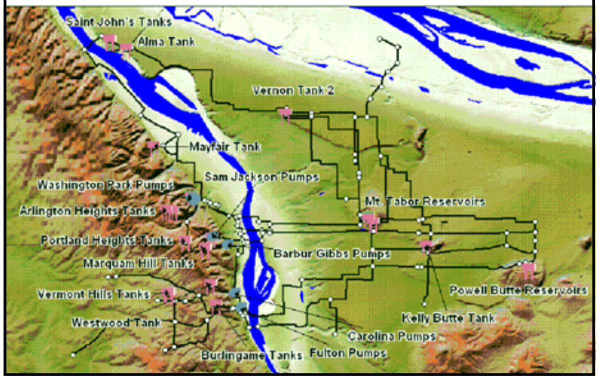
Moderately Liquefiable

Highly Liquefiable

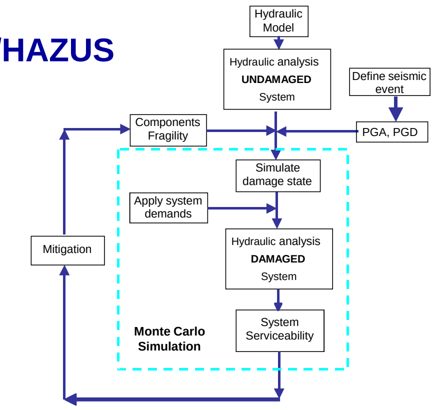


Burnaby Pipe Vulnerability for Design Basis Earthquake

Portland Water Bureau Distribution System GIS/HAZUS Modeled Network

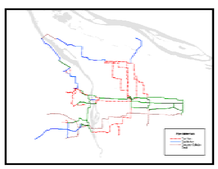


GIS/HAZUS

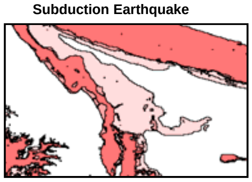


Portland GIS/HAZUS- Analysis Input

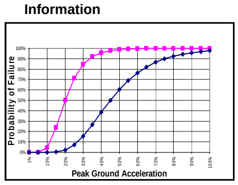
Ground Motion Scenario - Subduction Earthquake



Pipe Material/Facility Information



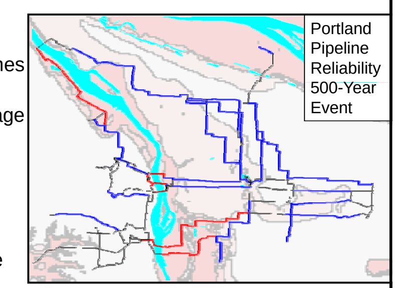
Liquefaction Susceptibility



Damage/Fragility Functions

GIS/HAZUS Output Portland Pipeline reliability in 500-Year Event

- Tank and reservoir pressures
- Pump station, tank, and reservoir flows
- Reliability of pump stations, tanks and reservoirs
- Importance of pipelines and components
- Pressure zone damage and serviceability
- Pipeline failure probability (worst performers)
- Pipeline reliability in 500-year earthquake



New Pipeline Design – Wave Propagation

- Confirm soils are competent and no permanent ground deformation will occur
- Check strain across joints/barrel
- Use ductile pipe systems - OK for all but extreme ground motions
- Segmented pipe with gasketed bell and spigot joints
  - Joint displacement relieves strain
  - Ductile iron or PVC
- Continuous pipe constructed with ductile materials
  - Steel with welded joints or polyethylene
  - Pipe barrel ductility accommodates strain

MMI

New Pipeline Design – Permanent Ground Deformation

- Quantify expected ground deformation
  - Fault crossings
  - Liquefaction/lateral spread
  - Settlement
  - Landslide
- Select pipe system to accommodate deformation
  - Steel with welded joints, restrained joint ductile iron
- Quantify pipe's capacity to deform
  - Design/detail accordingly
- Geotechnical improvements

MMI

New Pipeline Design – Permanent Ground Deformation - continued

- Design trench/vertical alignment to allow pipe movement
  - Shallow "V" trench
  - Backfill with light material
- Ductile material/restrained joints or continuous
  - DIP with restrained joints –
    - provide extension/compression capability (special fittings); calculate required displacement.
    - Install with restrained joints extended for thrust restraint required, intermediate position in other locations
  - Steel with welded or restrained joints
    - Do not use cement lining/coating – limits ductility
  - Polyethylene with fused joints

Geotechnical Mitigation

- Relocate
  - Different corridor with competent soils
  - Install below liquefiable layer (directional drilling)
- Stabilize alignment
  - Structural - retaining walls, pin piles
  - Geotechnical - stone columns, grout
- Sewer - flotation
  - Anchor pipe to stable soil layer using piles of screw anchors

System Upgrade Strategy

- Japanese are aggressively replacing CIP in poor soils.
- In U.S. replacement is difficult to justify economically on the basis of earthquake risk alone.
  - A study of the Portland Oregon system was not able to demonstrate a benefit-cost ration > 1 considering probabilistic earthquake exposure.
- Providing a hardened backbone supplemented by a system of pumps and hoses is often recommended in the U.S.
  - San Francisco and Vancouver have seismic resistant dedicated fire protection systems.
  - Contra Costa WD is hardening the backbone.

New Pipeline Design – Permanent Ground Deformation - continued

- Connections/Anchors
  - Avoid anchors (only possible on long straight runs with no connections)
  - Otherwise provide flexibility to allow differential movement (calculate required displacement)
  - Provide flexibility at connections to structures
- "Special" service connections
- Bridges - provide flexibility on both sides of the abutment, and at joints between spans.
  - Fill side of abutment to accommodate settlement
  - Span side of abutment to accommodate differential movement of span

Existing Pipe Mitigation Alternatives

- Replace existing pipe with ductile material and flexible restrained/welded joint design to reduce vulnerability
- Provide redundancy from multiple sources and/or feeds to critical locations
- Install/maintain isolation valves around vulnerable areas
- Emergency response (pumps and hoses)
- Improve capability for quick restoration
  - Material and equipment availability
  - Mutual aid

Conclusions and Recommendations

- Historically pipelines have been the weakest link in water system seismic performance.
- Quantify and map liquefaction hazards in the service area to use in developing a mitigation program.
- Quantify pipe vulnerability
- Water system distribution system mitigation strategies can include:
  - Upgrade the backbone system to provide a reliable way to supply water for fire suppression.
  - Develop the capability to use pumps and hoses in an emergency
  - Enhance system operational flexibility and control
  - Implement a long-term pipeline replacement program focusing on critical, vulnerable pipelines

Questions ?

Don Ballantyne
dballantyne@mmiengineering.com

MMI ENGINEERING