Water Pipe Replacement: Seismic and Aging

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Abstract

This paper presents a model to allow a utility to develop a cost effective long term program to replace older water pipes with new, seismic resistant water pipes.

Prior and after the recent 2010 Chile, 2010 Christchurch, 2011 Christchurch and 2011 Japan earthquakes, the various water utilities had opportunities to replace some water pipes with new seismic resistant pipes, either HDPE or DI with special joints; or make repairs with cut-in PVC or DI or steel pipes. In the post-earthquake rush to restore water service, most repairs were made as simply and as fast as could be done; meaning that many of the repaired pipes will break again in future earthquakes. We learn from these earthquakes that the time to make seismic upgrade is *not* right after the earthquake; but instead, seismic upgrades must be factored into long term (typically 10 to 50 year) capital improvement plans.

In the USA, the driving reason behind many long term capital improvement plans is pipe replacement due to aging. In high seismic zones in the USA, the seismic hazard is often neglected; but this practice needs to change in order to develop an optimal pipe replacement program. Still, the cost of replacing older water pipes is high and often cannot be justified by seismic reasons alone.

On a day-to-day basis, corrosion is attacking cast iron and other metallic pipes. This paper presents some recent research on the true performance of older cast iron and steel pipes in various types of soils.

A benefit cost model is presented that combines the effects from aging / corrosion and the effects from earthquakes to allow a water utility to cost-effectively plan a long term pipeline replacement program.

Key findings: (1). For cast iron pipe in non-corrosive soils, we found no evidence of any rapid increase in corrosion-related failures as the pipe gets older. (2) Using recent leak history and soil resistivity (R, ohm-cm), and seismic issues, one can use a benefit cost model to predict an economic life for every individual pipe in a water system, and a cost-effective pipe replacement program for the water system as a whole.

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Different American and Japanese Approaches

Soon after the 1989 Loma Prieta earthquake, the East May Municipal Utilities District (EBMUD) (water utility serving Oakland and 21 other cities and communities in the eastern portion of the San Francisco Bay Area) began a comprehensive seismic upgrade program for its water transmission and distribution systems. By 2011, EBMUD had spent well over $300,000,000 to address seismic issues alone. EBMUD has about 4,000 miles of transmission and distribution water pipes, serving 1,300,000 people. In the early 1990s, EBMUD recognized that it might suffer between 3,000 to 5,000 broken and leaking pipes in a large earthquake on the Hayward fault (annual chance about 1%); as of 2015, that estimate has increased to 6,000 pipe repairs or more. Except for upgrades for selected backbone pipes through fault crossing, liquefaction and landslide zones, none of the $300,000,000 was devoted to replacement of distribution water pipes. Therefore, EBMUD will still need to deal with repairs to potentially thousands of damaged pipes after a large future earthquake.

Since the 1995 Kobe earthquake, the JWWA (Japanese Water Works Association) issued updated seismic guidelines and pipe replacement guidelines. Since the issuance of these guidelines, several large Japanese water utilities have tackled this issue, refining these guidelines to be more like: replace older seismically vulnerable but less important pipes in 65 years, replace older seismically vulnerable and more important pipes in 40 years, and replace them with newer "seismically-designed" water pipes. In Japan, "seismically-designed" water pipes include ductile iron pipes with limited slip/rotation "chained" joints, or welded steel pipes. The Ductile Iron pipe manufacturers in Japan seem to be enjoying a re-birth of substantial water pipeline construction!

JWWA – AWWARF - WRF Seismic Workshops

After the disastrous 1995 Kobe earthquake (disastrous = major water outages of the water systems in cities of Kobe, Ashiya, and surrounding communities), coupled with the 1989 Loma Prieta and 1994 Northridge earthquakes, several of the affected water utilities, along with national water associations, JWWA and the American Water Works Association Research Foundation (AWWARF, now WRF) decided to hold bi-annual meetings. These meetings include Oakland, California (2013), Niigata, Japan (2011), Taipei, Taiwan (2009), with prior meetings held in Tokyo, Kobe, Los Angeles, and Oakland (2 times). At these meetings, it was observed that perhaps one of the most stark contrasts in technical approaches between Japan and the USA has been that Japanese utilities are spending large amounts of money to replace seismically-weak pipes (commonly on the order of $1,000,000,000 per large city), while American utilities are spending nearly nothing to replace seismically-weak pipes. Lively discussions between the workshop participants about these differing approaches have yielded the following key points:

- US water utilities would like to replace seismically-weak pipes, but the great cost involved mostly precludes such implementation.
- Japanese water utilities are following "JWWA" guidelines, and these require installation of seismically-designed water pipes. Some, but not all Japanese water utilities are implementing large scale pipe replacement programs.

Some US utilities are keen to consider "benefit-cost" approaches to the replacement of pipe. If the Benefit-Cost-Ratio (BCR) is greater than 1 (sometimes 2, 3 or 4), then these US water utility Boards of Directors can be willing to pass on the extra cost to customers.

Unlike Japan, in the USA there is no equivalent AWWA guideline that mandates replacement of older pipes on any specific aging schedule. Other code-setting agencies in the USA (such as the Uniform Building Code, the International Building Code, National Fire Protection Association, etc.) do not require water pipes to be installed with "seismic-details", even in the riskiest seismic areas (liquefaction, landslide or fault crossing locations). The recent earthquake in Napa (Eidinger et al, 2015) resulted in hundreds of water pipe repairs in Napa; yet gas pipelines in Napa, commonly in the same streets as the water pipes, required zero repairs. This proves that the pipe technology to install seismically "tough" pipes is available and practical. Yet for the most part, US water agencies are not installing seismically-tough pipes, nor, with very few exceptions, are they replacing older weak pipes with seismically-tough pipes. One goal of this paper is to outline a rational approach to accelerate such pipe replacement.

The American Lifelines Alliance (ALA) has issued a guideline on the seismic design of water pipes (2005); this guideline is non-mandatory. This guideline provides simple approaches (put any kind of pipe in the ground for the lowest cost in lower-risk areas, without any seismic design) to complex (critical non-redundant transmission pipes must be designed to rigorous seismic criteria). ALA allows that each utility may adjust the provisions based on "benefit-cost" considerations, so that additional costs would be warranted if serving high-economic value areas such as Silicon Valley, but zero-incremental costs would be warranted if serving rural residential areas where the incremental economic benefit of seismic-resistant pipes might be too small.

USA Asset Management

Over the past decade or so, the concept of "Asset Management" has gained some traction at water utilities in the USA. These concepts are described in AWWA (2006) and AWWARF-EPA (2005). Neither of these documents formally addresses seismic issues as one of the factors to be addressed in pipe replacement. The industry clearly needs better guidance on how to address seismic issues within the overall asset management effort.

Over the past 25 years, the common major US water utility has been replacing existing pipes at a rate of about 0.1% to 0.3% per year; a few replace at rates as high as 1% per year. This translates to about a 100 to 1,000 year replacement cycle. For example, EBMUD in the 1990s replaced about 5 miles of pipe per year, out of its 4,000 mile pipe inventory, which suggests an 800-year replacement cycle; a more modern strategy is being done to increase this to 10 to 40 mile per year replacement rate; using cost effective concepts. The big worry is that at some time, pipe leakage due to age-related issues will suddenly rapidly increase, overwhelming the owner's ability to repair, and resulting in many water outages and customer dissatisfaction.

Unless seismic issues are addressed, common US practice is to replace old pipes with newer commonly non-seismically-designed pipes. For example, it would be common to replace a 6" leaking 1920-vintage cast iron pipe with push-on caulked joints, with a 2015-vintage 8" PVC or Ductile Iron pipe with push-on rubber joints. In high seismic areas prone to soil failure, this practice is deficient.

If one simply assumes that there is truly a "100-year" lifetime for pipes, then most US water utilities are facing a huge increase in pipe replacement requirements over the next decade or so. For a moderately large utility, annual replacement costs will increase from about $7.5 million ($6 per capita) to perhaps $75 million ($60 per capita)[2]. In other words, the monthly water bill for a family of four will have to increase by about $17 per month. This represents a substantial rate increase, and might be politically unacceptable to publically-elected Boards of Directors or City Councils.

Some policy documents are saying that the pipe aging issue is a pending "CRISIS" or "CATASPROPHE". ASCE issues annual proclamations that the nation's infrastructure is in gross disrepair, and gives scopes like "C-" and "D-" for water[3] and wastewater buried pipe systems. Perhaps these are "scare" tactics? or, are these economically sound observations?

Pipe Replacement – The Benefit Cost Ratio (BCR) Model

The basic computation is to sum up the expected future benefits (= reduction in future repair costs should the pipe be replaced) divided by the replacement costs.

$$BCR = \frac{\sum_{i=1}^{n\,?\,years} ReducedRepairCostPerYear \Big/ (1+r)^{i}}{ReplacementCost}$$

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[2] These costs are based on an average fully installed cost of $1.500,000 per mile of 6-inch to 8-inch diameter pipe in moderately congested city streets.

[3] ASCE reports that the US "scorecard" for water and wastewater system infrastructure is "D" for 2013. See: http://www.infrastructurereportcard.org/drinking-water/, accessed February 28 2015.

where r = discount rate. A good Asset Management program should use this type of model to include both aging and seismic issues by summing up the BCRs for each pipe: $BCR_{Total} = BCR_{seismic} + BCR_{aging}$.

In this paper, we concentrate on how the key assumptions to compute BCR_{aging}.

For $BCR_{seismic}$, most of the details are outlined in FEMA (2001). The following paragraph highlights some of the key seismic assumptions:

For seismic mitigation, the long term approach is to plan to replace all pipes crossing zones subject to permanent ground displacements (PGDs), such as those from fault offset or liquefaction or landslide. The replaced pipes are assume to be designed to be able to withstand settlements due to PGDs (such as using ductile iron pipe with chained joints, fusion-butt welded HDPE pipe, or heavy-walled butt-welded steel pipe). Once these upgrades are in place, the annualized seismic losses will typically be reduced by about 90% (this realizes that there will remain some pipes that will still fail in future earthquakes, but that we have reduced the seismic risk by 90%).

Pipe Aging – Do Pipes Leak More as they Get Older?

When calculating BCR_{aging} for pipe aging, one must make assumptions about the rate of leakage as pipes age (get older). Lacking real data, most engineers assume that as pipes get older, they leak more. But, is this the "truth"? To apply some "facts" to this, we present in this paper some data for actual leak histories for the water system in Burbank, California. This water system has about 300 miles of pipe, with cast iron pipe being the most common pipe material, having an average age of more than 60 years. Figure 1 shows the actual pipe leak history for Burbank for the past 25 years.

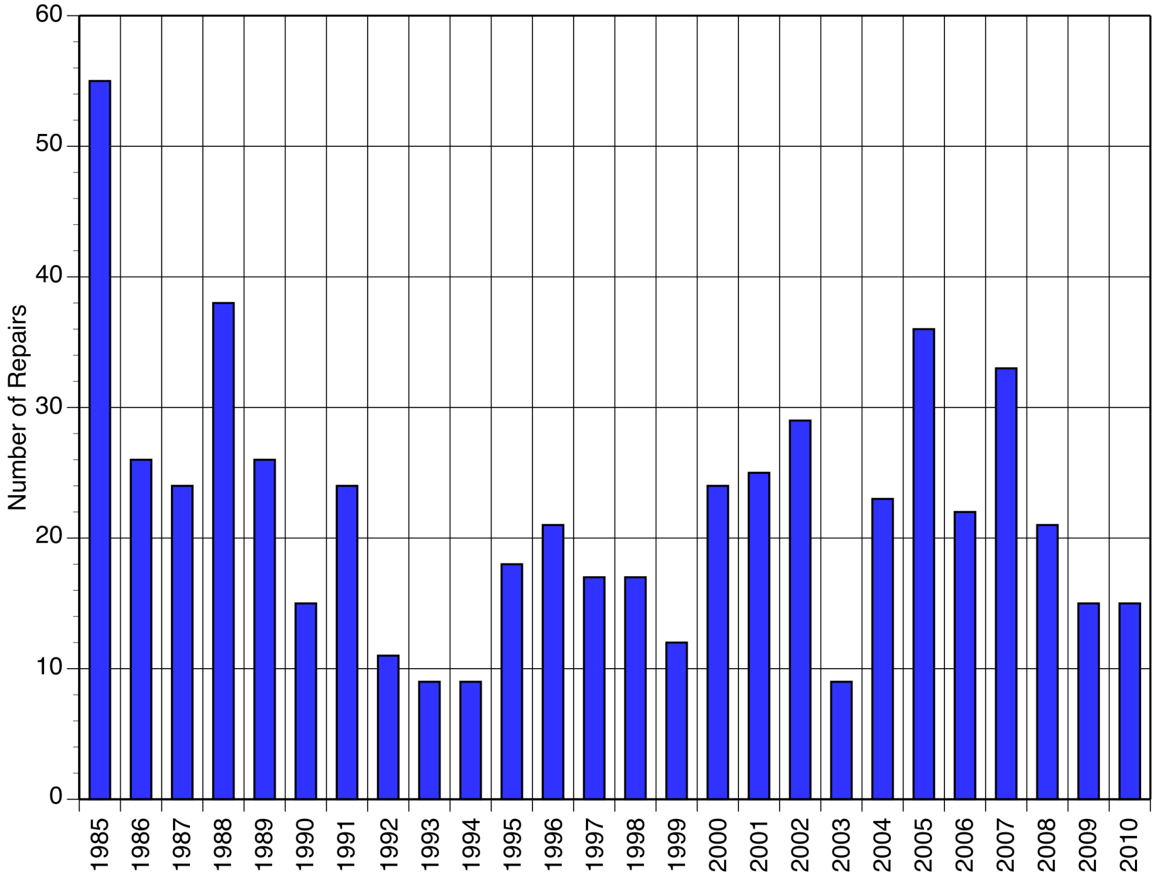

Figure 1. Leak History, 1985-2010. Burbank, California

For Burbank, the average repair rate has been 0.069 repairs / mile / year, with 16th to 84th percentile range from 0.038 to 0.100 repairs / mile / year. In North America, repair rates are commonly between 0.16 to 0.32 repairs per year per mile of water pipe, and more commonly in the range of 0.24 to 0.27.

Figure 2 shows the repair rate just for cast iron pipe. As shown in Figures 1 and 2, there is *no clear trend* to show that as pipes get older, they leak at a higher rate.

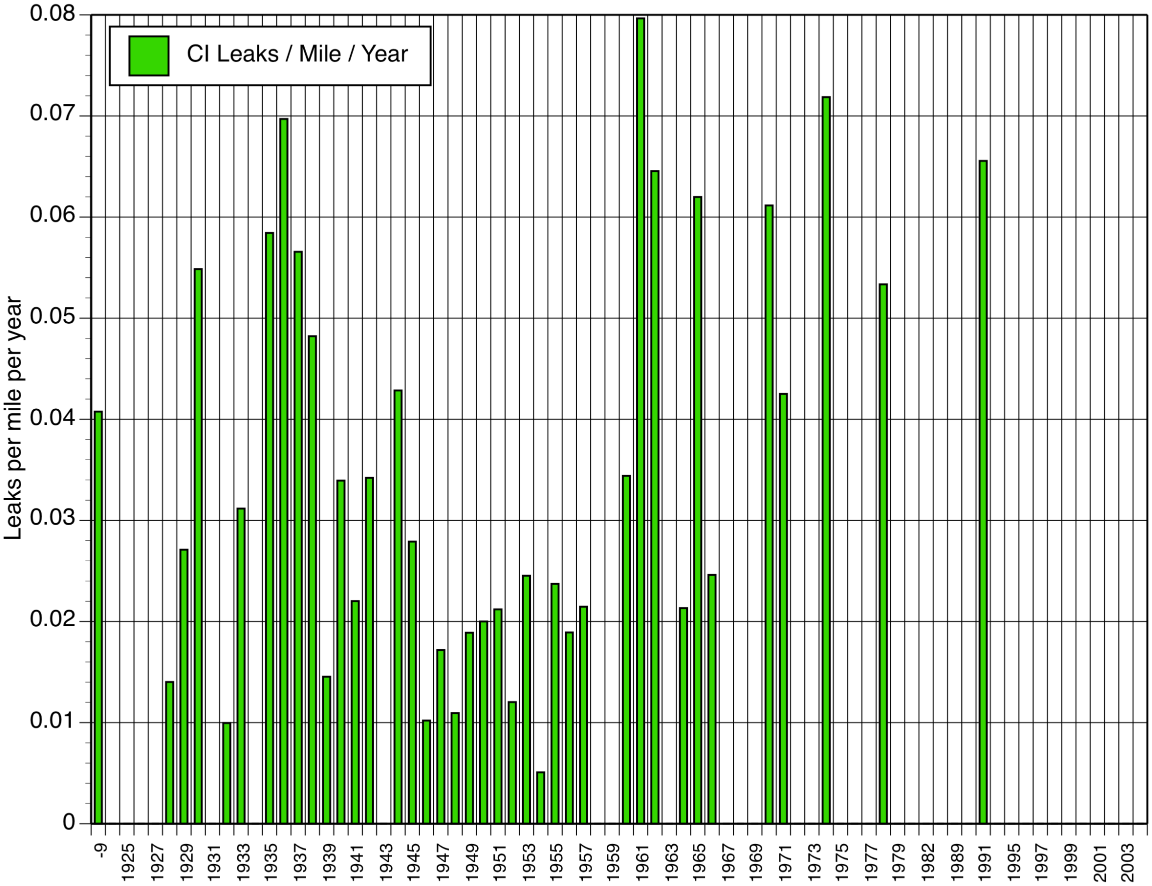

Figure 2. Cast Iron Pipe Repairs per Mile per Year, by Year of Installation.

We examined the seasonality of the repairs, by month. Figure 3 shows the results. The data is de-aggregated by type of pipe: Domestic (small diameter pipes from the meter to the house); Main (large diameter pipes in the street); Lateral (small lateral from the main to the meter); Main(R) (large diameter pipes in the street that have since been replaced); Lateral(R) (small lateral from the main to the meter, that have since been replaced).

Similar data for other water systems have shown some seasonality trends, suggesting that repair rates are highest when the ground is saturated (winter months) or when the ground is cold. Given the relatively deep ground water table for most of Burbank, as well as the limited rainfall, as well as the lack of frost heave / cold weather effects, we conclude that seasonality issues are not material to explaining the monthly variation in pipe repairs in Burbank; more likely, the scatter seen in Figure 3 is mostly random in nature.

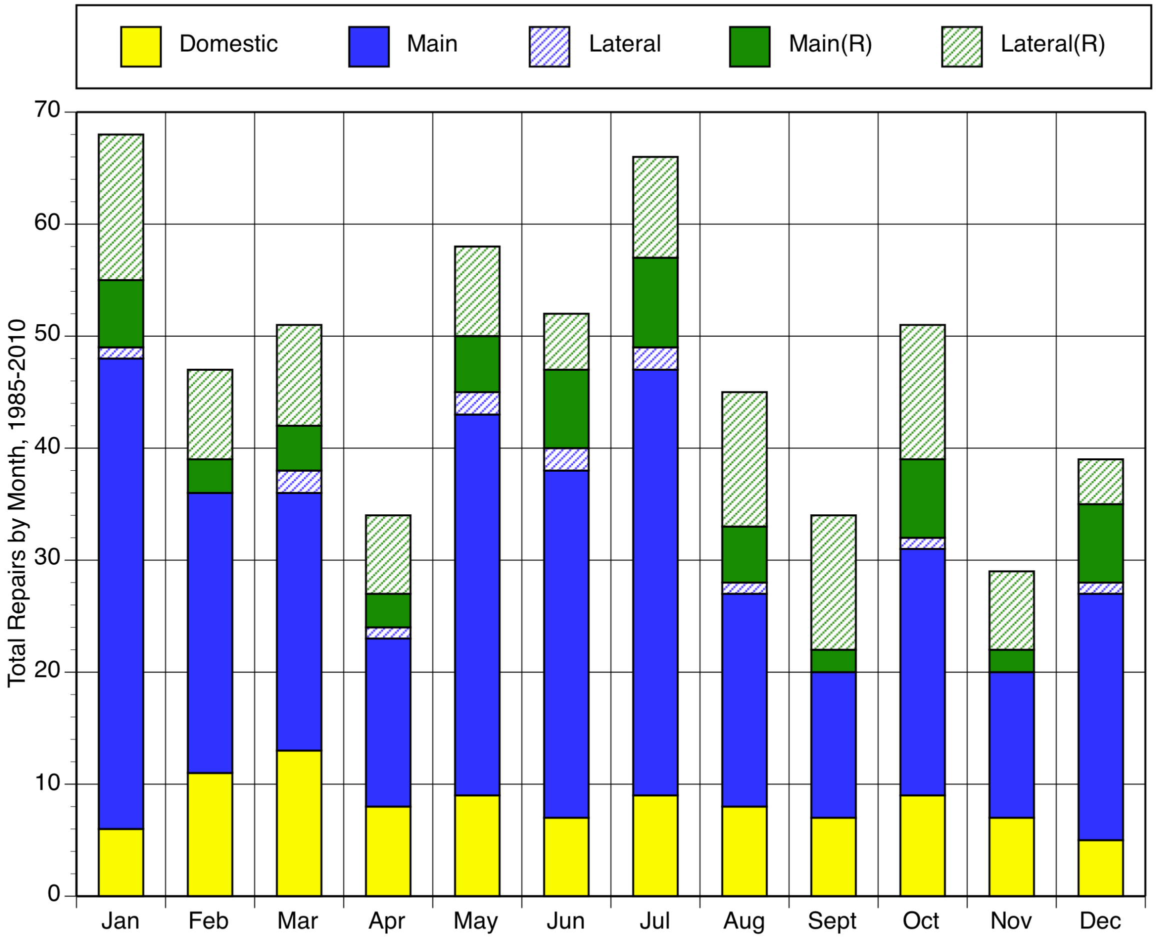

Figure 3. Repair Rate History, By Month, 1985-2010

Leak Rates – Soil Resistivity

The overall leak rate (0.069 leaks / mile / year) for Burbank's water mains are rather low by industry standards (0.24 to 0.27 leaks / mile / year). To further examine the reasons for this low leak rate, a soil-resistivity test program was conducted, so that we could quantify the effect of soil resistivity (R, ohm-cm) versus the observed long term pipe leak performance in Burbank. A total of 86 Wenner 4-point tests were performed, at locations roughly equally spaced throughout Burbank. We assigned the tested R values (ohm-cm) to each individual pipe.

Figure 4 shows the length of pipe, versus R values for each kind of pipe main. The vertical scale is shown as a "log" scale, so that it is easier to see the actual lengths of pipe for small values. The scale ranges are:

- R = 1,500 to 3,000 ohm-cm. Highly corrosive. (0.1% of total)
- R = 3,000 to 5000 ohm-cm. Corrosive. (0.7% of total)
- R = 5,000 to 10,000 ohm-cm. Moderately corrosive. (11.0% of total)
- R = 10,000 to 20,000 ohm-cm. Mildly corrosive. (35.3% of total)

- R > 20,000 ohm-cm. Essentially non-corrosive. (52.9% of total)

The pipe types are: CCP (large diameter concrete cylinder pipe), CI (cast iron); CU (copper laterals); DI (Ductile Iron); GLV (small diameter galvanized steel); HDPE (high density polyethylene); RCP (reinforced concrete cylinder); SS (special steel with push on gaskets, often 2" to 4" diameter); STL (steel, often 2" to 6", some >12" diameter).

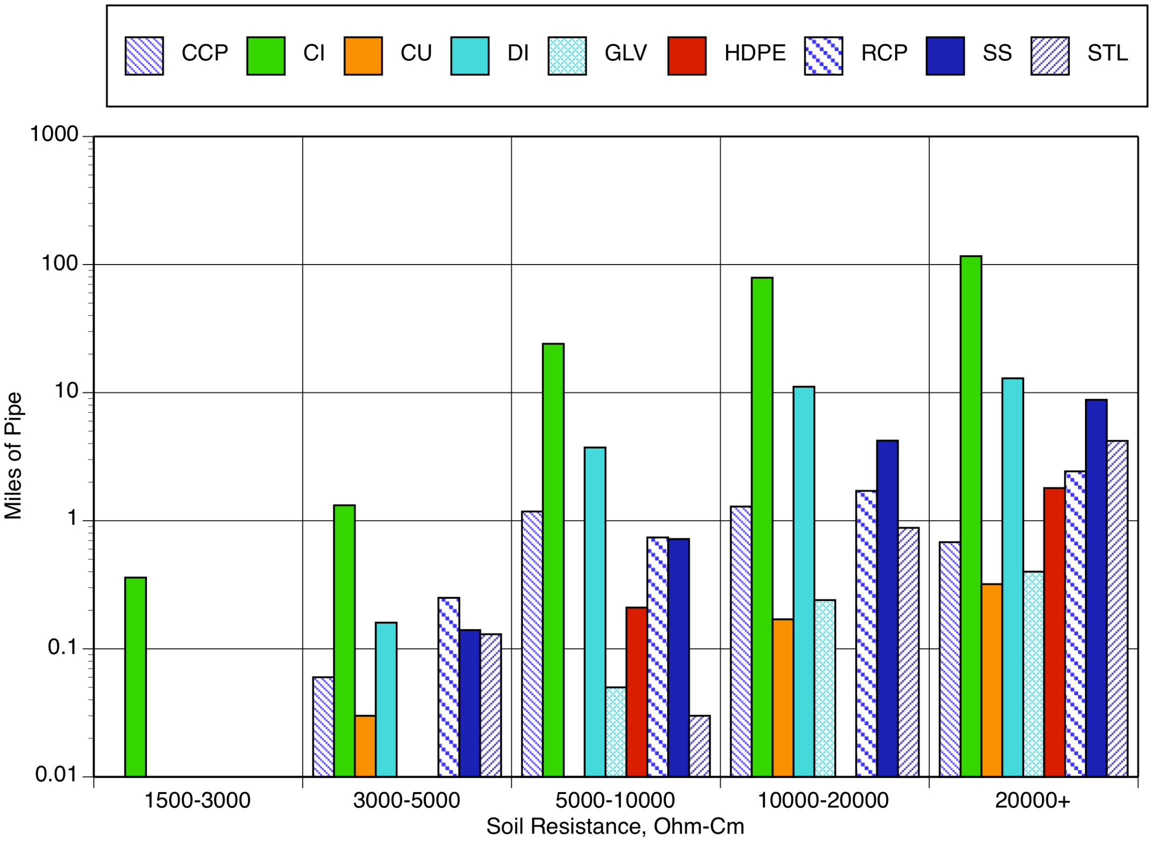

Figure 4. Miles of Pipe, by R, by Type of Pipe

Table 1 lists the variation of R versus the relative leak rates for the kinds of pipe with the highest leak rates (CI, SS, STL). For example, a SS pipe situated in soils with R between 5,000 to 10,000 ohm-cm is 3.31 times as likely to have had repairs than the "average" pipe in the city (which is set to 1.00).

R Range (ohm-cm)	Percentage of all pipe	Percentage of all repairs	Relative Weakness All pipe	Relative Weakness CI	Relative Weakness SS	Relative Weakness STL
1,500 – 3,000	0.1	0.0	n.a.	n.a.	n.a.	n.a.
3,000 – 5,000	0.7	0.7	0.90	1.01	n.a.	0.0
5,000 – 10,000	11.0	17.8	1.62	1.88	3.31	24.9
10,000 – 20,000	35.3	29.6	0.84	0.67	1.54	0.0
20,000 +	52.9	51.9	0.98	1.04	0.57	1.09

Table 1. Relative Weakness of Pipes, by R

Type / Diameter	CCP, RCP	HDPE	CI	CU	DI	GLV	SS, STL (≤12")	STL (>12")
Any	0.015	0.010	0.030	0.150	0.015	0.600	0.500	0.015
1" to 2"		0.010	0.400	0.150	0.015	0.600	0.500	
4"		0.010	0.150		0.015	0.600	0.500	
6"		0.010	0.030		0.015		0.500	
8" – 12"	0.015	0.010	0.020		0.015		0.500	
16" – 30"	0.015	0.010	0.020		0.015			0.015

Table 2. Leak Rate Factor k_1 (Diameter vs. Leaks / Mile / Year)

Type / Age (Years)	CCP, RCP	HDPE	CI	CU	DI	GLV	SS, STL (≤12")	STL (>12")
Any	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0 to 20	0.90	0.95	0.90	0.75	0.80	0.80	0.80	0.90
20 to 40	1.00	1.00	0.95	1.00	1.00	1.00	0.90	0.95
40 to 60	1.10	1.05	1.00	1.25	1.10	1.00	0.95	1.00
60 to 80	1.15	1.10	1.25	1.50	1.15	1.20	1.00	1.00
80 to 100	1.20	1.15	1.50	2.00	1.25	2.00	2.00	1.10
100 +	1.50	2.00	2.00	2.50	2.00	2.50	2.50	1.30

Table 3. Leak Rate Factor k_2 (Age vs. Leaks / Mile / Year)

Type / Resistance (Ohm-cm)	CCP, RCP	HDPE	CI	CU	DI	GLV	SS, STL (≤12")	STL (>12")
Any	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1500-3000	1.50	1.00	1.50	2.00	1.25	2.00	2.00	1.25
3000-5000	1.10	1.00	1.10	1.25	1.10	1.25	1.25	1.10
5000-10000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000-20000	0.90	1.00	0.90	0.90	0.90	0.90	0.90	0.90
20000+	0.90	1.00	0.90	0.90	0.90	0.90	0.90	0.90

Table 4. Leak Rate Factor k_3 (Soil Resistance vs. Leaks / Mile / Year)

Given the test data and leak history, we developed a pipe aging model (Leak rate per mile per year) for Burbank as follows:

$$Leak\ \ Rate_{aging} = k_1 k_2 k_3 \text{ (generic, leaks per mile per year)}$$

where k_1 is the leak rate for the type of pipe (diameter, pipe barrel material), $k_2$is the adjustment to consider pipe age, and k_3 is the adjustment to considered local soil resistivity (Tables 2, 3, 4). For pipes with known leak history, the leak rate is taken as either its average over the entire history of documented leaks (past 25 years), or since

2003, whichever is higher[4]. The final leak rate for any individual pipe that is used in the computation of BCR_{aging} is the *higher* of the generic leak rate or the pipe-specific leak rate.

Benefit Cost Analysis Examples

Table 5 shows two example calculations of BCRs. A complete discussion of this model follows FEMA (2001).

Parameter	MainID	MainID	Units
MainID	7	4326	
Length	928.72	185.17	Feet
Year installed	1991	1971	
Age	20	40	Years
Material	CI	CI	
Diameter	6	4	Inches
Soil resistance	17402	28421	Ohm-cm
Liquefaction susceptibility	L	H	Low, High
Fault susceptibility	VL	VL	Very Low
Background repair rate	0.0243	0.1283	Repairs / mile / year
Number of Leaks	1	0	Sine 1985
Number of recent leaks	1	0	Since 2003
De-facto repair rate[5]	0.1290	0.0045	Repairs / pipe / year
Outage time	6.79	6.05	Hours
Outage Length	750	500	Feet
Replacement Cost	$83,585	$11,110	
Repair cost per year	$516	$18	
Claim cost per year	$52	$2	
GDP loss per year	$312	$3	
Sales loss per year	$1	$0	
Repair costs per year (E)	$882	$23	Existing Pipe
Material Replacement Pipe	DI	HDPE	
Repair costs per year (R)	$22	$2	Replaced Pipe
NPV, Reduced repair costs	$19,455	$475	
BCR, Aging	**0.233**	**0.043**	
Losses per year, Seismic (E)	$72	$977	Existing Pipe
Losses per year, Seismic (R)	$7	$98	Replaced Pipe
NPV, Reduced seismic costs	$1,465	$19,893	
BCR, Seismic	**0.018**	**1.791**	
BCR, Aging + Seismic	**0.250**	**1.833**	
Result	**Do not replace**	**Replace**	

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[4] The most recent repair rate, namely within the past 7 years, is believed to be a better proxy for ongoing aging / ground movements that are damaging the pipe than the long term repair rate. For example, if a 1-mile long pipe had 0 repairs between the date of its original installation, say 1935, to 2003, but had 2 repairs between 2003 and 2010, the recent repair rate (2/7, or 0.29 repairs per mile per year) is a better indicator of ongoing issues than the long term repair rate (2/75).

[5] The de-facto rate is the background rate, the recent rate, or the computed rate adjusted for pipe material, diameter, age and soil R value.

Table 5. Examples

Table 5 shows various parameters used to calculate the BCR ratios for two pipes. GDP = gross domestic product. GDP loss = economic loss to customers when the pipe is shut down due to leak. NPV = net present value. Claim costs are the costs due to inundation from leaking pipes. Sales loss is the loss of revenue to the water utility when they cannot sell water. Outage length = distance along pipe between valves that must be closed while making the repair.

Benefit Cost Results

The benefit cost model was used to rate the priority for pipe replacement for the water system in Burbank, California. The key findings of the benefit cost analysis are as follows:

- **Pipe Aging**. 1.56 miles of pipe in the system are current candidates (BCR ≥ 1) for replacement, *for aging alone*.
- **Pipe Seismic**. 10.96 miles of pipe in the system are current candidates (BCR ≥ 1) for replacement, *for seismic alone*.

Recommendations

For cities like Burbank, the long term (one hundred years from 2015 to 2115) pipe replacement strategy should look something like the following:

Seismic. Replacement pipes in areas zones with moderate to high or very high liquefaction / landslide threat, or traverse active faults, should be seismically designed per ALA 2005. This is true in high seismic risk California (San Francisco, Los Angeles), Kodiak (Alaska), La Malbaie (Quebec) or more moderate seismic risk areas like San Diego, Memphis, Salt Lake City, Portland, Seattle, Vancouver (British Columbia). The decision of when to replace should be based on recent leak history, not on seismic risk alone. In extremely high seismic hazard areas (Eureka California, many areas of Japan), the decision of when to replace pipe might be justified on seismic issues alone.

Aging. Pipes with a known leak history with more than 2 (or 3) leaks within the past 5 years should be high priority for early replacement (within the next ten years). This reflects a variety of benefit cost analyses, and a "willingness to pay" concept. There appears to be a fairly high correlation of the locations of on-going leaking pipes and the locations of high seismic pipeline vulnerability.

Old Pipes. Pipes without a recent leak history should be "left in place" without a specific schedule for replacement. Only in extremely high seismic risk areas, or for critical non-redundant pipes, should pipe replacement be done primarily for seismic reasons.

Other Issues. Pipes that require replacement due to inadequate fire flows, tuberculation, taste or odor, high leak rate, or other reasons, should be replaced with suitable pipe materials per ALA 2005 or similar seismic guidelines. In a nutshell, if the pipe to be replaced is not exposed to ground failures, then "push on joint" pipes (lower cost) are acceptable, while important pipes exposed to liquefaction should have "restrained" or "chained" joints, while important pipes subject to fault offset should be designed to accommodate the fault offset. For pipes in landslide zones, avoidance is the primary solution (zone the area as not fit for permanent or important facilities); but for existing landslide zones the solution is generally "buyer beware" and the water utility should not have to design to accommodate landslide other than to prescribe restrained joints; and customers in landslide zones must accept the higher risk for damage to water pipes and relatively poor post-earthquake performance. All new pipes should be designed with suitable corrosion protection. The seismic performance of aged (over 40-years) thin-walled ductile iron pipe, with or without "external baggies", located in corrosive environments, is currently unknown.

Simple replacement rules like: "replace all cast iron pipe installed prior to 1935" are not supported by the facts. Local corrosion cells or weak soils or locally high pressure, or local installation practices, may have much more influence on pipe vulnerability and leakage than the type and age of pipe in general.

Limitations

The data presented in this paper are for Burbank California. The model and trends are specific to the actual geologic conditions in Burbank. Generally, these are characterized as granular soils with a deep water table, with non-corrosive soils being the common environment. While the benefit cost model is robust and can be used in any locale, the model data that goes into the BCR model (Tables 1, 2, 3, 4) should *not* be used for locations with high ground water tables, or for locations with soils with low R values, or for pipes with water quality chemistry prone to interior corrosive attack (common pH less than 7), or in soils best characterized as clayey.

Units and Conversions

The data presented in this paper uses US customary units. Conversions are as follows: 1 mile = 1.6 km; 1 inch = 25.4 mm; 1 mile = 5,280 feet; 1 foot = 12 inches; the cost to install one mile of pipe per "inch-foot" is computed as: 5,280 feet (1 mile) * nominal diameter (in inches) * units cost per inch-foot.

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