Pipe Replacement Strategies for Aging and Seismic Issues

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ABSTRACT

This paper describes the water pipeline replacement program for the City of Palo Alto, California water department. The city has about 236 miles of pipe, including older cast iron pipe installed nearly 100 years ago; mostly asbestos cement pipe installed 40 to 70 years ago, and ductile iron, HDPE, PVC, concrete cylinder pipe and mortar lined and coated steel pipe.

A pipeline replacement program was developed that factors in ongoing pipe aging issues and pipe seismic vulnerability. The program uses a benefit cost test, for each pipe, to establish the cost effectiveness of pipe replacement, individually for aging, and individually for seismic issues. The benefit cost ratios are added together to develop a city-wide balanced pipe replacement program.

By adopting this type of model, a water utility can develop a rational cost effective approach to water pipe replacement. For Palo Alto, the model shows that the annual capital expenditures could be re-allocated to higher priority pipeline replacement, and in fact, a case could be made to slow down the pipe replacement program.

INTRODUCTION

Beginning in the 1990s, the City of Palo Alto water department began a long term effort to replace water pipes, called the Water Main Replacement Program (WMRP). The work was originally planned out in 34 phases, with each phase generally being accomplished in about 1 year. By 2014, Phases 1 through 24 were essentially complete. In 2015, it was decided to review the approach for future Phases 25 through 36.

This paper suggests that, going into the future, a different pipe replacement strategy might be adopted. It became evident that Phases 1 through 24 had already replaced many of the most leak-prone and deteriorated pipes; while most of the remaining pipes planned to be replaced in future Phases 25 through 34 are currently functioning as expected and have never leaked in the past two decades.

Given the analyses presented in this paper, a new pipe replacement program includes about 13.5 miles of pipe, of which 2 miles are in deteriorated condition, 10 miles of pipe are seismically weak, and about 1.5 miles of pipe will deteriorate over the next decade to the point where they warrant replacement. The estimated cost for this pipe replacement program is $2.92[1] million (aging) plus $19.01 million (seismic) plus $2.3 million (future deteriorated pipe) or about $24.23 million in total. The recommended pipe replacement program (13.5 miles) is about half the originally-planned effort (27.5 miles) over the next decade. This recommended pipe replacement program would reduce the capital requirements for pipeline replacement over the next decade, while still cost effectively addressing ongoing aging of pipes and seismic risks in Palo Alto.

This new pipe replacement program is based on the following principles:

- All of Palo Alto's existing water pipes are aging. Many of these pipes continue to perform their function with little to no maintenance, and have adequate seismic capability if they are located in soils that are not prone to significant seismically-induced ground deformations.

- Most water pipes should not be replaced until such time that they sustain sufficient deterioration as to make them unreliable. Other pipes, located in soils prone to liquefaction, landslide or surface faulting, could be cost-effectively replaced with suitably seismic-designed pipes, if the existing pipe's failure in earthquakes will result in high adverse economic impacts to Palo Alto's customers.

- The expenditure of current capital dollars for pipe replacement should be balanced against the benefit of fewer day-to-day leaks as well as fewer damaged pipelines in future earthquakes.

- It is current US national policy that the cost to repair damage caused by future major earthquakes to Palo Alto's water system will be reimbursed at about a 75% rate by FEMA. To the extent that the current cost for Palo Alto to mitigate seismic impacts exceeds the future benefits, this paper suggests that it is more cost effective for Palo Alto to accept the impacts of some level of seismic damage, and make repairs after the earthquake, the cost of which will be substantially reimbursed by FEMA.

- This paper provides quantified valuation of the cost effectiveness for replacement for each pipe. This is done by computing a benefit cost ratio (BCR) for each pipe, for pipe replacement due to aging issues, for pipe replacement for seismic issues, and for both issues combined. This report uses the combined BCR of 1 to set the dividing line as to which pipes should be currently replaced (1 or higher) or left in service (under 1). Should Palo Alto wish to be more risk adverse, then more length of pipe can be replaced, by selected a lower BCR dividing line value.

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[1] All costs presented in this paper are in constant $2015, and exclude the effects of inflation.

WATER SYSTEM DESCRIPTION

Figure 1 shows the Palo Alto water system (see G&E 2015 for comprehensive description). The system is divided into 9 pressure zones. Zone 1 is the largest zone, located near San Francisco bay. Zones 2 through 9 are at progressively higher elevations, with the San Andreas fault located at the southwest edge of Zone 9. Stanford University is located in the area between Zones 2 and 3.

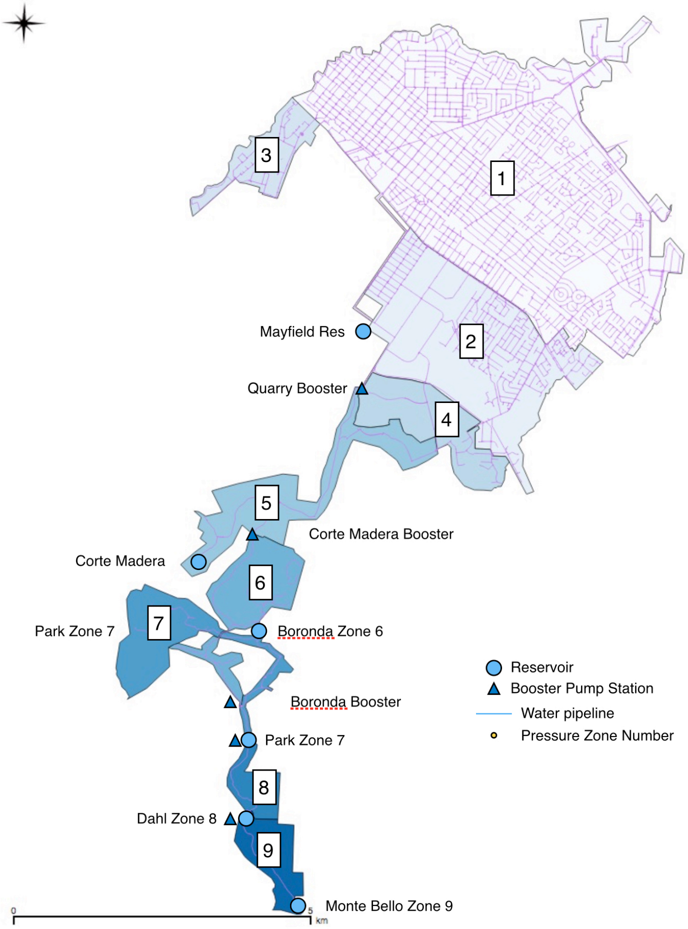

Figure 1. Palo Alto Water System

Table 2 lists the length of pipe mains by diameter and material. This table excludes service and hydrant laterals. Table 2 excludes a small percentage of pipe with other pipe materials or with unknown diameter. As can be seen, AC pipe is the most common material in the modern Palo Alto water system.

SOIL RESITIVITY

A soil-resistivity test program was conducted, so that we could quantify the effect of soil resistivity (Rho, ohm-cm) versus the observed long-term pipe leak performance in Palo Alto. A total of 71 Wenner 4-point tests were performed on March 4, 9 and 16, April 13, 2015 at locations roughly equally spaced throughout Palo Alto. Figure 2 shows the locations of the tests (colored dots), with the computed Rho values for the soil layer at 5 feet beneath grade indicated by the colors. We assigned the tested Rho values (ohm-cm) to each individual Palo Alto pipe main using a distant-weighted average of the five closest Rho tests.

Diam. (inch)	Cast Iron (feet)	Asbestos Cement (feet)	CCP (feet)	PVC (feet)	DIP (feet)	HDPE feet)
2	964	710		571		
4	3,447	37,794		955	199	
6	55,193	313,788		153,265	3,002	1,819
8	27,505	214,376	4	41,280	8,319	40,442
10	10,530	29,116	60	12,775	2,526	2,149
12	9,567	72,984	626	15,092	7,499	2,138
14	557	22,572	10,870		68	2,725
16	735	18,137	27,671	4	164	4,546
18	1,304		2,459		9	
20			5,969		189	
24		25	2,130		5,827	
27	3,717	2,770	4,000			
30			1,895		5,956	
Total (feet)	113,568	712,392	55,684	224,247	33,821	53,819
Total (miles)	21.51	134.92	10.69	42.47	6.41	10.19

Table 2. Length of Pipes, Primary Pipe Materials and Diameters

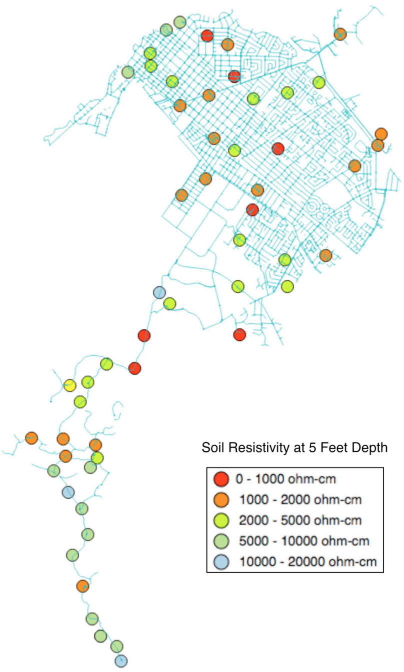

Figure 2. Soil Rho Test Values (5 feet depth)

The usually interpretation of Rho for metal pipe is as follows:

- R = 500 to 1,500 ohm-cm. Extremely corrosive.
- R = 1,500 to 3,000 ohm-cm. Highly corrosive.
- R = 3,000 to 5,000 ohm-cm. Corrosive.
- R = 5,000 to 10,000 ohm-cm. Moderately corrosive.
- R = 10,000 to 20,000 ohm-cm. Mildly corrosive.
- R > 20,000 ohm-cm. Essentially non-corrosive.

Figure 3 shows the length of pipe, versus Rho values for each kind of metal 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.

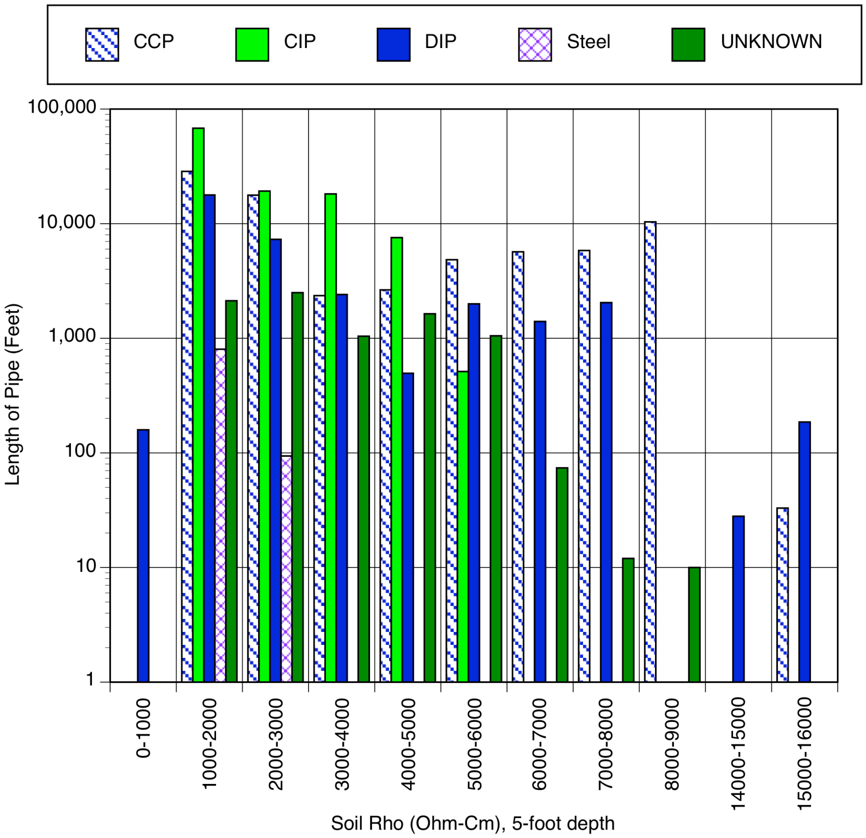

Figure 3. Soil Rho at Pipe (5 foot depth) (Metal Pipe only)

PALO ALTO INCOME

For purposes of benefit cost analyses, the economic impacts of disruptions to the water supply are needed. We describe the general economic activity in Palo Alto, zip codes 94301 and 94305. The Gross Regional Product (GRP) of Palo Alto is much higher than the per capita average for the State of California as a whole, or about $9.441 billion, or a daily GRP of $9.441 billion / 365 days = $25,865,753 per day.

SEISMIC EVALUATION

Based on its record of historic earthquakes and its position astride the North American - Pacific plate boundary, the San Francisco Bay region, within which the City of Palo Alto is located, is considered to be one of the more seismically active regions of the world. During the historical period (approximately 170 years), faults within the region have produced 14 moderate to large magnitude ($M > 6$) earthquakes affecting the Bay Area, as well as many significant smaller magnitude ($5 < M < 6$) earthquakes. We evaluated the Palo Alto water system for 24 different earthquakes. We considered ground shaking, liquefaction, landslide and surface faulting hazards. Table 3 lists the key findings.

EQ	Fault	M	Number of Pipe Repairs	Percentage of Palo Alto Customers with Water
1	San Andreas Santa Cruz	6.9	3.8	100.0 %
2	San Andreas Peninsula	6.0	5.1	98.4
3	San Andreas Peninsula	6.2	14.4	96.5
4	San Andreas Peninsula	6.4	29.3	87.6
5	San Andreas Peninsula	6.6	45.0	71.6
6	San Andreas Peninsula	6.8	60.9	57.0
7	San Andreas Peninsula	7.0	78.7	56.2
8	San Andreas SAN+SAP+SAS	7.2	77.2	57.0
9	San Andreas SAN+SAP+SAS	7.4	125.0	34.4
10	San Andreas SAN+SAP+SAS	7.5	139.5	34.3
11	San Andreas SAN+SAP+SAS	7.7	168.6	26.9
12	San Andreas SAN+SAP+SAS	7.9	198.3	23.6
13	San Andreas SAN+SAP+SAS	8.0	215.2	19.8
14	Hayward N+S	7.25	53.7	59.6
15	Hayward South	6.8	24.2	91.6
16	Hayward North	6.8	3.0	100.0
17	West Napa	6.0	0.0	100.0
18	Rodgers Creek	7.0	2.1	100.0
19	Calaveras North + Central + South	7.2	31.0	75.9
20	San Gregorio	7.7	77.8	57.0
21	Mount Diablo Thrust	6.5	2.1	100.0
22	Monta Vista	6.8	92.0	55.5
23	Greenville	7.0	3.5	100.0
24	Zayante – Vergeles	6.9	3.2	100.0

Table 3. Pipeline Performance, 24 Scenario Earthquakes

The details of the seismic analyses are presented in (G&E 2015), and are adapted from ALA (2001), updated to reflect recent findings from the Napa 2014 earthquake. Earthquakes on the San Andreas fault (especially events that simultaneously break the North Coast + Peninsula + Santa Cruz segments, SAN + SAP + SAS) pose the largest risk to Palo Alto. The right-most column in Table 3 reflects the de-pressurization of the water system due to leaking water mains and service laterals. EQ 1 represents a repeat of the historic 1989 Loma Prieta earthquake.

With respect to the water system, there are two important time intervals after the earthquake:

- First 24 hours. During this time frame, the chance of a fire ignition is highest. The fire ignition model (marked "2012", orange line) in Figure 4 was adopted to forecast the number of ignitions in Palo Alto. Note that recent earthquakes around the world have shown that the ignition rate is much lower than what was adopted by HAZUS (EBMUD, black line), largely reflecting that many of the "black square" empirical data points from the 1906 San Francisco earthquake reflects styles of construction (coal burning fireplaces, weak unreinforced masonry buildings, etc.) that is no longer prevalent.

- Should an ignition occur, and the initial ignition is not controlled by local residents within a few minutes, the fire can spread within a structure, and if left uncontrolled, can spread into the wildland and to adjacent structures.

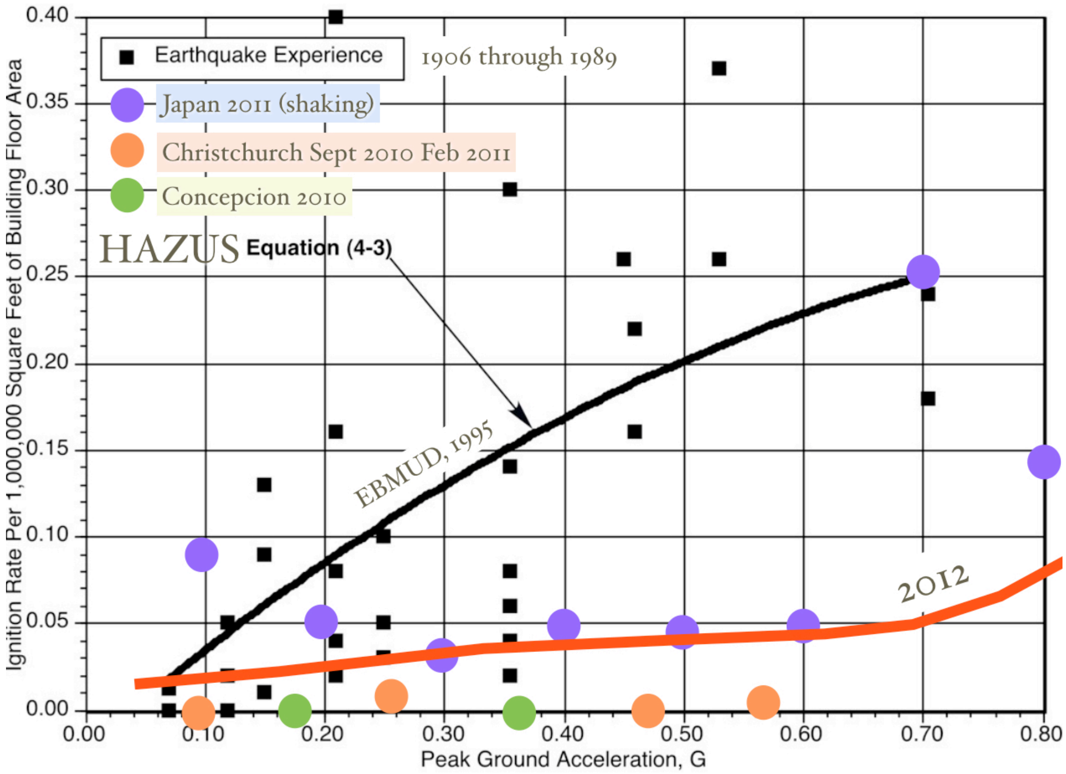

Figure 4. Fire Following Earthquake Ignition Rate – Empirical Evidence

PIPE AGING EVALUATION

We analyzed a history of 1,101 pipe repairs in the Palo Alto water system. The oldest repair was dated March 12, 1990, and the most recent repair was September 24, 2014. The database reflects 24.58 years of data. Table 4 shows the 282 repairs on currently (2015) active pipe mains. Table 5 shows the leak rate per mile per year.

Diam (inches)	ACP	CCP	CIP	DIP	PVC	Total
4	24		1			23
6	109		34		8	151
8	48		12			60
10	8		7			15
12	18		4	1	1	24
14	3		1			4
16		3				3
Total	210	3	59	1	9	282

Table 4. Leak Repairs in Past 24.58 Years on Active Pipe Mains

Diam (inches)	ACP	CCP	CIP	DIP	PVC
4	0.125		0.062		
6	0.076		0.132		0.007
8	0.048		0.094		
10	0.059		0.143		
12	0.053		0.090	0.029	0.014
14	0.029		0.386		
16		0.023			
Total	0.064	0.012	0.112	0.006	0.006

Table 5. Historical Repair Rates by Pipe Material and by Pipe Diameter (for Active pipes)

In the bottom row of Table 5, the "total" repair rate is for all leaks on that type of pipe, divided by the total length of all diameters of that pipe; this value is not the average of the above rows, as there are some pipe diameters with no pipe repairs. Regressions were made using the data in Table 5 to develop an "average" leak rate by material, with a multiplier (k1) to adjust for diameter. Table 6 relates the repair rate by pipe type by diameter.

We also examined the rate of pipe repairs by age of pipe. Figure 5 shows results for AC pipe. The key findings are as follows: ACP in Palo Alto has had, so far, a long-term average repair rate of about 0.065 repairs per mile per year; there is strong evidence that smaller diameter ACP (4") has had nearly twice the repair rate than larger diameter ACP; there is weak evidence that older ACP has a higher repair rate than younger ACP; at least in Palo Alto. Tables 7 and 8 show similar factors to adjust for pipe age and soil Rho.

Diam (inches)	ACP	CCP	CIP	DIP	Steel	PVC
Average	0.064	0.012	0.112	0.006	0.150	0.006
<4	2.0	1.0	1.4	1.2	4.0	1.1
4	2.0	1.0	1.4	1.2	2.0	1.1
6	1.1	1.0	1.2	1.2	1.0	1.1
8	0.9	1.0	1.0	1.1	0.8	1.0
10	0.8	1.0	0.9	1.0	0.7	0.9
12	0.7	1.0	0.8	1.0	0.6	0.8
14	0.6	1.0	0.7	0.9	0.6	0.8
16	0.5	1.0	0.6	0.9	0.5	0.8
18	0.5	1.0	0.5	0.8	0.5	0.8
20	0.5	1.0	0.5	0.7	0.5	0.8
24	0.5	1.0	0.5	0.6	0.5	0.8
27	0.5	1.0	0.5	0.6	0.5	0.8
30	0.5	1.0	0.5	0.6	0.5	0.8

Table 6. Leak Rates by Pipe Material and by Pipe Diameter (k1)

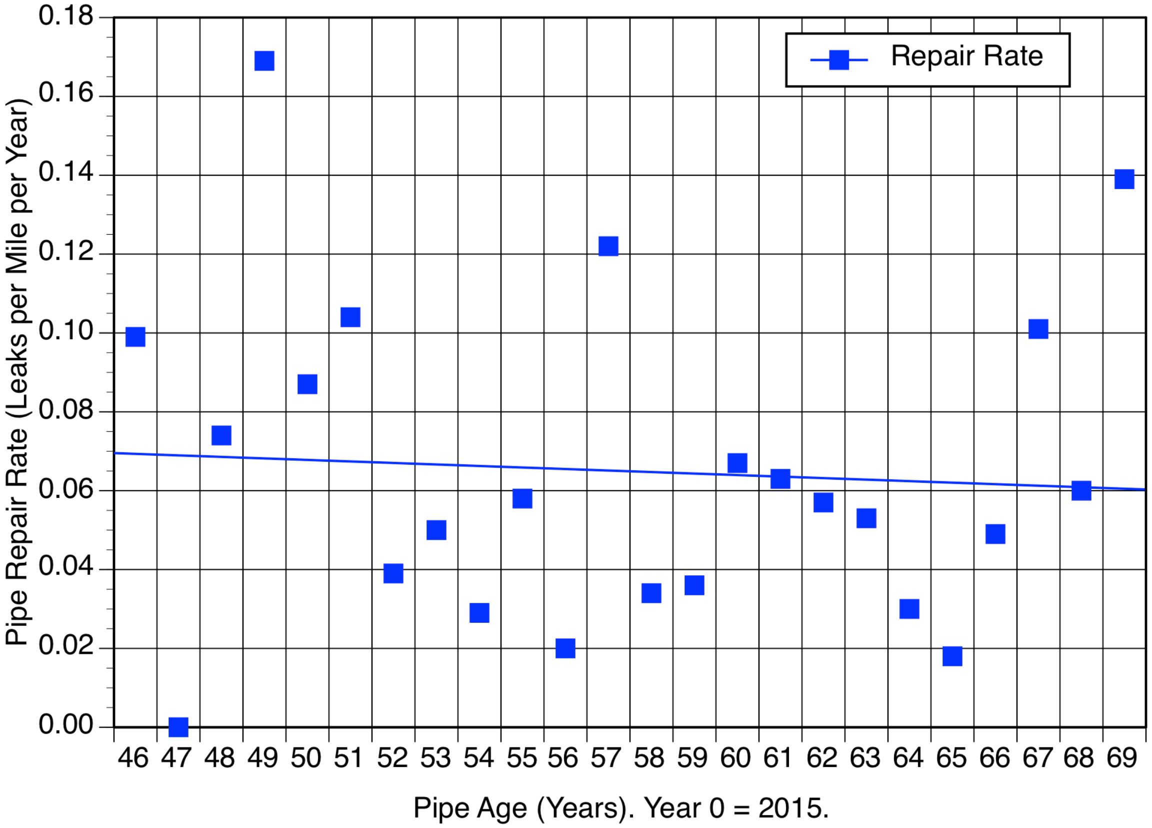

Figure 5. Repair Rate and Pipe Length, ACP, versus Age (1945-1969)

This last point is of crucial importance. Many pipe replacement strategies are based on using pipe age as an important (along with pipe material and diameter) factor in deciding whether or not to replace a pipe. This concept assumes that as pipes get older the cumulative effects of internal and external corrosion should lead to pipe wall thinning; and with sufficient pipe wall thinning, the internal water pressure (including effects of cycling) will eventually burst the pipe. While we agree that this may be the common case for metallic pipe (CIP, DIP, Steel, CCP, etc.), the factual evidence in Palo Alto, for ACP, does not support this finding, at least not yet.

Pipe Age (Years)	ACP	CCP	CIP	DIP	Steel	PVC
Average	1	1	1	1	1	1
1-10	0.4	0.8	0.5	0.8	0.8	0.9
11-20	0.6	0.8	0.6	0.9	0.8	0.9
21-30	0.8	0.8	0.7	1	0.9	1
31-40	1	0.8	0.8	1	0.9	1
41-50	1.2	0.8	0.9	1.1	0.95	1
51-60	1.2	0.9	1	1.1	0.95	1.1
61-70	1.2	1	1.2	1.15	1	1.1
71-80	1.2	1.1	1.4	1.2	1.2	1.1
81-90	1.4	1.2	1.6	1.3	1.4	1.2
91-100	1.6	1.2	1.8	1.4	1.6	1.2
101-110	1.8	1.3	2	1.5	1.8	1.2
111-120	2	1.4	2	1.7	2	1.2
>120	2	1.5	2	2	2.5	1.2

Table 7. Leak Rates by Pipe Age, Active Mains (k2)

Soil Resistivity ohm-cm	**Rho Factor, CIP**	**Rho Factor, DIP**	**Rho Factor, CCP**	**Rho Factor, Steel**
1,000	1.2	1.1	1.1	1.15
2,000	1.1	1.0	1.0	1.1
3,000	0.8	1.0	1.0	1.0
4,000	0.7	1.0	1.0	1.0
5,000	0.6	0.9	0.9	0.9
6,000 +	0.5	0.9	0.9	0.9

Table 8. Soil Resistivity Factors for Pipe Repairs (k3)

BENEFIT COST MODEL

A Benefit Cost Ratio model is used to sort out which pipes are most cost effective to be replaced. We consider two main reasons for pipe replacement:

- The pipe has had a high historic rate of leak, with each leak requiring a repair. The cost of the day-to-day repairs, as well as the economic impacts to customers while the repair is being made, influences whether it is cost effective to replace the pipe.

- The pipe has a high chance of being damaged in future earthquakes. The cost of the post-earthquake repairs, as well as the economic impacts to customers while the repair is being made, coupled with an increased chance of fire spread, influences whether it is cost effective to replace the pipe.

The basic computation for a Benefit Cost Ratio (BCR) is to sum up the expected future benefits (= reduction in future repair and economic costs should the pipe be replaced) divided by the current replacement costs.

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

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: $BCR_{Total} = BCR_{seismic} + BCR_{aging}$.

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

$Leak\ \ Rate_{aging} = k_1 k_2 k_3$ (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 6, 7, 8). For pipes with known leak history, the leak rate is taken as either its average over the entire history of documented leaks (past 24.58 years), or in the prior 7 years, whichever is higher. 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.

Table 9 presents the results, using different BCR ratios as a cut off.

BCR Criteria	Num Pipes	Length (Feet)	Length (Miles)	Replacement Cost for Length
BCR leak > 1.5	22	1,565	0.30	$499,180
BCR leak > 1	40	3,934	0.75	$1,098,920
BCR leak > 0.6	54	6,762	1.28	$1,743,850
BCR seismic > 1.5	349	95,930	18.17	$24,505,553

BCR Criteria	Num Pipes	Length (Feet)	Length (Miles)	Replacement Cost for Length
BCR seismic > 1	432	111,368	21.09	$30,494,724
BCR seismic > 0.6	472	120,725	22.86	$36,191,045
BCR total > 1.5	374	97,654	18.50	$25,039,400
BCR total > 1	475	114,291	21.65	$31,289,500
BCR total > 0.6	533	125,502	23.77	$37,624,230

Table 9. Pipe Lengths and Costs with Various Benefit Cost Ratios

The bottom line of the BCR evaluation for aging is that the City of Palo Alto's current plan to replace an average of 2 to 3 miles of pipe per year for aging for the next decade or so may be "too much", given the generally low rates of repairs seen since records have been kept (1990 onward).

LIMITATIONS

The data presented in this paper are for Palo Alto California. The model and trends are specific to the actual geologic conditions in Palo Alto. Generally, these are characterized as clayey soils, locally granular, with a shallow water table, with moderately 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 6, 7, 8) should *not* be used for locations with differing conditions, or for pipes with water quality chemistry prone to interior corrosive attack (common pH less than 7).

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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References 1, 2, 3 are available at: http://www.geEngineeringSystems.com.