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PRIORITIZATION OF PIPELINE REPLACEMENT BASED ON FAILURE RATE

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The purpose of this paper is to prioritize water pipelines for replacement through the analysis of pipeline failure rates and reliability. By using actual pipe condition record data from Honolulu Board of Water Supply (BWS), the constant failure rate is recognized through Bathtub profile and used to calculate reliability. This paper provides the utility manager a quantitative method to evaluate and arrange pipeline renewal. It assists in determining maintenance schedules depending on the age and type of the pipe by plotting the corresponding failure rate against time. Reliability helps determine whether a certain group of pipes are within the acceptable practice threshold to signal replacement. In this paper, the analysis of four major types of pipe systems from BWS are conducted. With the data from fiscal year (FY) 2008, the failure rates are calculated, and the reliability of all pipelines are seen to be above 80%.

Keywords: Reliability, Bathtub curves, Water supply, Main breaks, Length in ground.

1 INTRODUCTION

According to the AWWA (2001), water is the most capital intensive of all utility services. As the pipelines need to be buried underground, the costs of management and maintenance are always high. It is very important to catalogue the pipe type, age and length in the area under scrutiny, and undertake prediction analysis for pipe replacement. As such, a proactive approach of pipe asset management is crucial for determining the optimal time to replace a pipe.

In this article, the actual pipe condition in fiscal year (FY) 2008 provided by the Honolulu Board of Water Supply (BWS) is used. BWS serves approximately one million customers with over 150 million gallons of water daily (BWS Report 2010), maintaining more than 2,000 miles of pipelines, which break at a rate of approximately one per day. By analyzing the failure rate of pipelines, the paper can provide the utility manager to prioritize the pipe replacement.

2 METHODOLOGY

The study of pipeline replacement prioritization has been conducted and published by various researchers and scholars. For example, by matching the threshold and predicted break rates, Loganathan *et al.* (2002) derived the method to predict optimal renewal time for pipe systems. Rogers and Grigg (2009) combined the probability models and the ranking systems to determine the possibility of pipe failure. Wood and Lence (2009) used statistical deterministic equations to estimate the pipe failure rate.

In this study, pipes with similar characteristics (i.e. type and age) are grouped and used to form reliability distributions. Furthermore, the constant failure rate period is identified by using the bathtub curve for reliability calculations.

2.1 Failure Patterns for Complex Products

Complex products often follow a familiar pattern of failure (Juran and Gryna 1993). When the failure rate is plotted against a continuous time scale, the resulting graph (Figure 1) known as the "bathtub curve", exhibits three distinct periods. The first period, known as the early life phase, is characterized by high failure rate right after installation, due to faulty installations or defective pipe. The second period, or useful life phase, is characterized by a constant low failure rate. The failure rate increase in the third period, wear-out life phase, is caused by pipe deterioration and ageing.

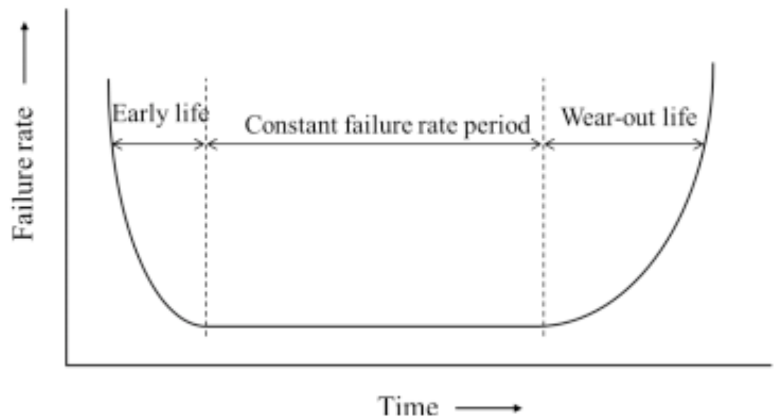

Figure 1. The theoretical bathtub curve.

"The bathtub curve is a fundamental tool in quality engineering for analyzing the failure process. When the failure rate is constant, the distribution of time between failures is distributed exponentially." (Juran and Gryna 1993) This is the basis of the exponential formula for reliability, requiring a comprehensive work log to verify.

2.2 Reliability Formula

The distribution of time between failures indicates the chance of failure-free operation for the specified time period. By plotting the bathtub curve, the early and wear-out periods can be easily filtered; only the constant failure rate λ in the useful life period is considered; the probability of reliability can be estimated by the exponential formula in Eq (1) (Juran and Gryna 1993).

$$R = e^{-t\lambda} \quad (1)$$

Where, R is probability of failure-free operation for a time period equal to or greater than t
λ is failure rate in the constant period
t is a specified period of failure-free operation

3 BWS PIPE SYSTEM OBSERVATION

To gain an understanding of the water supply pipe system at BWS, data was collected from inventory records, annual reports, statistical summaries, and main break data from fiscal year (FY) 2008. Based on total length of pipe in the ground (LIG), the four major types of pipe are, in order of prevalence, cast iron (CI), ductile iron (DI), polyvinyl chloride (PVC), and concrete cylinder (CC). These four types account for 90% of the pipe system; the other 10% are asbestos concrete (AC), steel (STL), copper (CU), as illustrated in Figure 2.

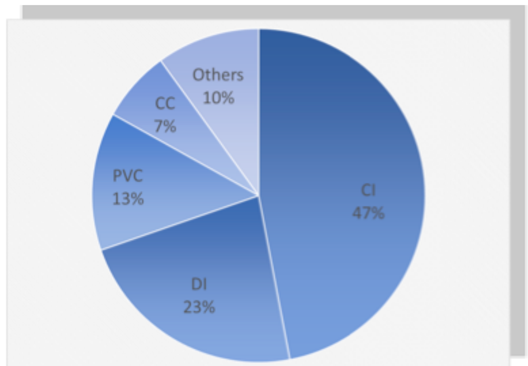

Figure 2. Percent of total length of all types of pipes in FY2008.

The pipes ranged in age from new to over 100 years, with the average age of all pipes in FY 2008 being approximately 32.2 years. The oldest pipe in the system was installed in 1898; pipes between 40 to 50 years were the most prevalent, comprising approximately 16.1 percent of the total population. For each pipe type, the average age varies. By FY 2008, the average age of CI pipes was 46.7 years; 16.6 years for DI pipes; 9.5 years for PVC pipes; and 32.3 years for CC pipes, shown in Figure 3.

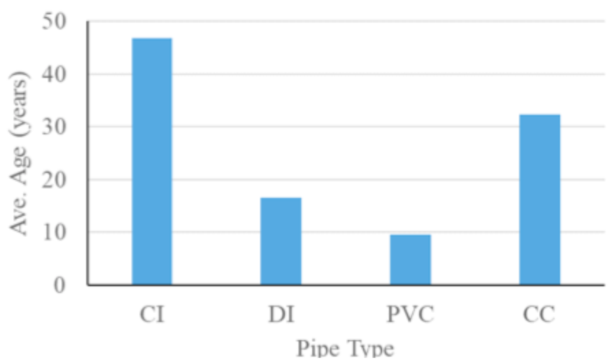

Figure 3. Average age of all types of pipes in FY2008.

3.1 Failure Rate and Future Breaks

The following equation calculates failure rate:

$$Failure\ rate = (Number\ of\ breaks)/LIG/mile \quad (2)$$

The failure rate was calculated by using number of breaks in a specific age group divided by the length of pipe in the ground (LIG). The unit of failure rate is breaks/year/mile.

Tables 1-4 summarize the number of failures and the LIG for each four-major pipe types in FY 2008. The number of failures and the LIG for each pipe type was grouped into ten-year intervals, with the exception of PVC pipes, which were grouped into subsequent five-year intervals, because they are relatively new and installed only recently in the system. For each pipe type, assuming the failure rate of each age group remains constant, the expected annual failure rates after 20 years are forecast based on the current statistical data from FY2008. It is noticeable that, after 20 years, CI and DI pipes will face a larger volume of failures; the number of annual failures will increase by 70% and 863%, respectively.

Table 1. Failure rate for CI pipes by age in FY 2008 (Modified from Singh and Adachi 2013).

Age	Number of failures	LIG (miles)	Failure rate (breaks/yr/mile)	LIG (miles) after 20 years	Expected annual failures after 20 years
0-10	0	0.0	-	-	-
10-20	0	0.0	-	-	-
20-30	1	0.2	6.311	0.0	0.0
30-40	30	163.2	0.184	0.0	0.0
40-50	49	244.0	0.201	0.2	0.0
50-60	43	222.4	0.193	163.2	31.5
60-70	23	90.9	0.253	244.0	61.7
70-80	26	97.6	0.266	222.4	59.2
80-90	13	31.6	0.411	90.9	37.4
90-100	1	1.5	0.647	97.6	63.1
100-110	12	4.3	2.809	31.6	88.8
Sum	198	-	-	-	341.9

Table 2. Failure rate for DI pipes by age in FY 2008 (Modified from Singh and Adachi 2013).

Age	Number of failures	LIG (miles)	Failure rate (breaks/yr/mile)	LIG (miles) after 20 years	Expected annual failures after 20 years
0-10	1	100.8	0.010	-	-
10-20	13	200.6	0.065	-	-
20-30	6	123.5	0.049	100.769	4.9
30-40	9	33.8	0.266	200.578	53.4
40-50	1	1.0	1.031	123.473	127.3
50-60	2	0.6	3.621	33.783	122.3
Sum	32	-	-	-	308.0

Table 3. Failure rate for PVC pipes by age in FY 2008 (Modified from Singh and Adachi 2013).

Age	Number of failures	LIG (miles)	Failure rate (breaks/yr/mile)	LIG (miles) after 20 years	Expected annual failures after 20 years
0-5	4	87.9	0.046	-	-
5-10	3	78.8	0.038	-	-
10-15	0	65.9	0.000		0.0
15-20	0	24.3	0.000	78.8	0.0
20-25	1	13.1	0.076	65.9	5.0
Sum	8	-	-	-	5.0

Table 4. Failure rate for CC pipes by age in FY 2008 (Modified from Singh and Adachi 2013).

Age	Number of failures	LIG (miles)	Failure rate (breaks/yr/mile)	LIG (miles) after 20 years	Expected annual failures after 20 years
0-10	0	3.9	0.000	-	-
10-20	1	25.6	0.039	-	-
20-30	1	19.6	0.051	3.9	0.198
30-40	2	40.6	0.049	25.6	1.261
40-50	2	52.2	0.038	19.6	0.750
Sum	6	-	-	-	2.209

It is predictable that the replacement of certain pipes is very necessary. Due to the relative recent installations of PVC and CC pipes, the failure rate of these two pipe types will become constant in 20 years.

3.2 Bathtub Curves

Taking a glance at the Tables 1-4, CI pipes have the longest age range; while PVC pipes have the shortest. Due to the relatively new pipeline system and material of the pipe, the number of failures were only eight and six for PVC and CC pipes, respectively. Detailed observations and comparisons from the Bathtub curves are discussed below.

Bathtub curves for four types of pipes are shown in Figure 4. It is observed that the curves of CI and DI were the only two that fell into the theoretical Bathtub curve, where the constant failure rate periods were recognized in the graphs. Some portions of the Bathtub curve for PVC pipes were recognized as the Bathtub profile. Since the PVC pipes were relatively new and the total numbers of failure were low in FY 2008, the results are inconclusive and will not be considered for replacement at this moment. Finally, the Bathtub curve for CC pipes was inverted to the opposite of the bathtub profile. Since CC pipes have the lowest failure rate and shortest LIG, CC pipes will also have low priority for replacement compared to CI and DI pipes.

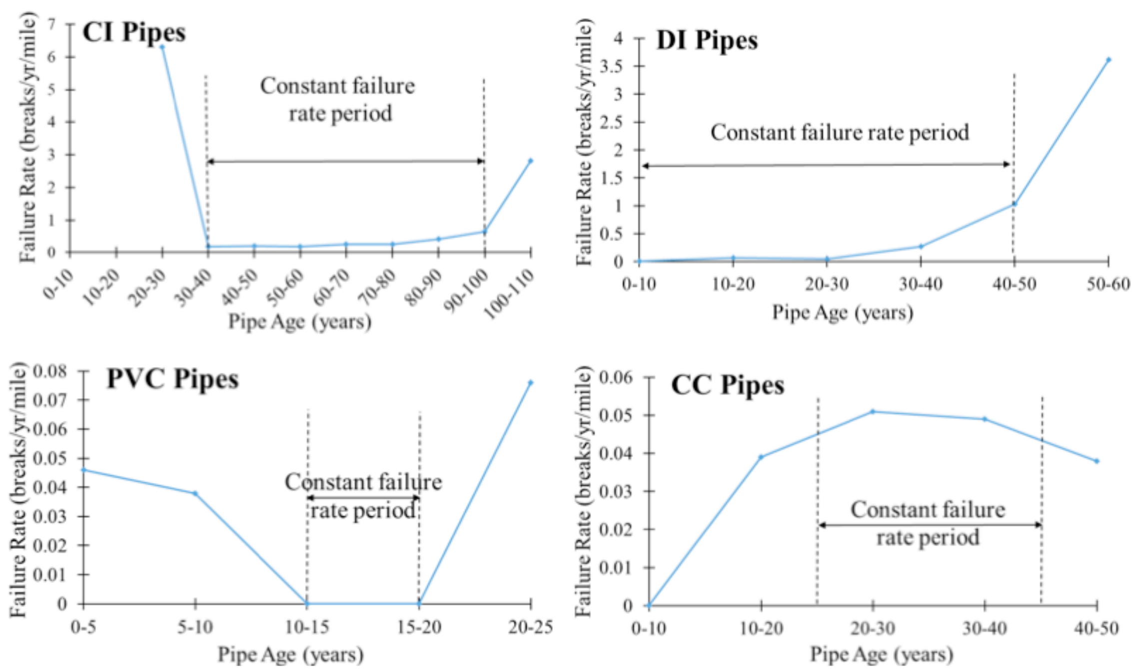

Figure 4. Failure rate vs. Time plot for four types of pipes in FY 2008.

4 RELIABILILTY FOR BWS PIPE SYSTEM

Once the constant failure rate periods are identified for CI and DI pipes, the average failure rates are computed by using total numbers of failure divided by the total LIG in the age groups within the constant failure rate, which is 30-100 year for CI pipes and 0-40 year for DI pipes. Furthermore, this average failure rate is the λ in Eq. (1).

The reliabilities for CI and DI pipes were calculated using Eq. (1). Set t equal to 1 for the FY 2008 reliability rate calculations. Results are shown in Table 5. It can be seen from Table 5, in

FY 2008, CI pipes have a 19.5% rate of failure in one year, while DI pipes have as low as 6% of the chance.

Table 5. Reliability in FY 2008.

Pipe type	Constant failure rate period	Average failure rate	Reliability ($R = e^{-t_{\lambda}}$)	Probability of failure
CI	30-100	0.217	0.805	0.195
DI	0-40	0.063	0.939	0.061
PVC	10-20	0	1	0
CC	25-45	0.046	0.955	0.045

After the calculation, the BWS utility manager will use the calculated reliability to make the pipe replacement decision. Furthermore, an experienced manager will also cross-reference the previous record to evaluate the necessity of pipe replacement for certain types of pipes in particular field areas. For budgeting purposes within that fiscal year, based on the reliability, the manager is now able and ready to recommend the priority of pipe replacements.

5 CONCLUSIONS AND LIMITATIONS

The overall goal of this paper was to provide an assessment of the pipe system at BWS and a guidance for the utility manager to prioritize the replacement of pipelines. The methodology is straightforward and can be done by anyone even without an engineering background. Based on the data collected in FY 2008, the major observations are as follow:

- The failure rate v. time plot of CI pipes fits the Bathtub profile quite typically, establishing a visible constant failure rate period, allowing reliability to be calculated.
- In FY 2008, it was discovered that CI pipes had the highest average failure rate, followed by DI and CC pipes; PVC pipes showed zero average failure rate.
- High breakage of CI and DI pipes is predicted for FY 2028, and these two types of pipes are recommended to have the highest priority for replacement; PVC and CC pipes have low probability of failure and have low priority for replacement.

The reliability analysis provides a guideline and sound methodology for prioritization of pipeline replacement. Due to the lack of data from BWS, this paper provided an approximate method in 2008 to predict the future performance of pipelines. Therefore, this study needs to be continually undertaken every year for multiple years to achieve adequate statistical data and set a reference database for more accurate future breakage predictions.

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