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Economic analysis of water main breaks

Thomas M. Walski and Anthony Pelliccia

The cost of water main breaks can represent a significant portion of a distribution system's maintenance costs. Although qualitative guidance is available on why pipes break and when they should be replaced, there are no universal quantitative rules for when to replace pipe. This paper gives a simple method for determining which pipes need to be replaced, based on the history of recorded breaks.

Water distribution systems have a finite life. As pipes age, they lose their carrying capacity and become prone to breakage. There comes a time when it is more economical to replace a pipe than to repair it. Many cities, especially older ones in the Northeast, are having to deal with the high breakage rates typical of decaying systems. Unfortunately, little quantitative information is available to help water utilities determine precisely when a pipe should be replaced.

The distribution system for the city of Binghamton, N.Y., is more than 100 years old and experiences pipe failures each year. In an effort to upgrade the system at the lowest possible cost, the state of New York asked the Baltimore district of the US Army Corps of Engineers to conduct an urban water supply system study for Binghamton.

Baltimore district personnel inventoried the mains in the system, giving special attention to the number of pipe failures. With the use of a computer data base they prepared tables on the characteristics of the system and a report that summarized the occurrence of breaks for each pipe within the system. The report also offered some insight into the probable cause of the varying rates at which breaks occur (e.g., breaks resulting from severe cold weather between the months of November and April or breaks that occurred in pipes located in heavy traffic areas). The Baltimore district then asked the US Army Engineer Waterways Experiment Station (WES) to conduct a study to develop guidelines for replacing or repairing pipes and to project the costs to maintain the integrity of the system.

Objective and approach

The objective of this work was to produce a method that would enable the technical personnel employed by the city of Binghamton to: (1) decide whether a pipe should be replaced or repaired, (2) estimate the expected replacement cost, and (3) estimate the expected repair cost. The basis for deciding whether to repair or replace pipe is the present worth of costs for repair and replacement. First, the occurrence of breaks in a pipe is projected. Then the costs are calculated and compared with the cost of replacing the pipe. In this article a model is developed to predict pipe breaks as a function of pipe age, type of pipe, diameter, occurrence of previous breaks, and temperature. The costs and break prediction model are combined to project the costs of repairing main breaks over the next 20 years. Finally, another rule is developed to identify which pipes should be replaced in the near future.

<table>
<thead>
<tr>
<th>Pipe Diameter</th>
<th>Cost ($/ft)</th>
<th>Cost ($/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>in.</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>8</td>
<td>20.8</td>
</tr>
<tr>
<td>200</td>
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<td>62.2</td>
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<tr>
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<td>22</td>
<td>69.8</td>
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</tbody>
</table>
leakage, which eroded the bedding, were the primary break-causing factors.

A recent study of pipe breaks conducted in the Cincinnati, Ohio, area by Clark et al.\textsuperscript{1} found that the age of metallic pipes (cast iron and steel as opposed to reinforced concrete) was an important factor in determining the time elapsed to the first repair and in determining the number of breaks. These investigations also found the corrosivity of the soil, pressure in the pipe, and land use to be important factors.

Morris\textsuperscript{11} gave the rule of thumb that if three or more breaks occurred per 300 m (1000 ft) of pipe (23.4 breaks/km or 15.8 breaks/mi), the pipe should be replaced. Since this was presented in a manual, the analysis used to derive the rule was not cited nor was any mention made as to whether the breaks would occur over the life of the pipe or in one year. For a pipe of less than 99.9 m (333 ft), the rule dictated that the pipe should be replaced if one break occurred.

The increase in the rate of pipe breaks with age is generally attributed to strength reduction as a result of corrosion. Romanoff\textsuperscript{10} and Gerhold\textsuperscript{10} reported on the loss of weight and pitting in metallic pipes over a period of years in varying soil environments. Fitzgerald\textsuperscript{11} showed that corrosion-induced breaks increase exponentially over the life of a pipe, while breaks resulting from other causes do not vary greatly with pipe age.

The Cast Iron Pipe Research Association (CIPRA)\textsuperscript{12} gives five criteria that indicate whether metal pipes will be subject to external corrosion, soil resistivity, pH, redox potential, sulfides, and moisture. Appendix A to ANSI/AWWA Standard C105-77\textsuperscript{4} presents a procedure for determining whether a soil is corrosive enough to require protection of pipe.

The pipe break data analyzed by the Baltimore district showed that more breaks occur during the winter months. This is to be expected since the soil in Binghamton is highly permeable, and the severe winters can result in deep frost penetration. Increased soil movement and increased loads on pipes occur when soil freezes.\textsuperscript{2,3,4} Smith\textsuperscript{5} showed that loads on pipe can double when frost penetrates close to the top of the pipe.

When replacement criteria were determined for the Los Angeles water system, Lane and Buehring\textsuperscript{6} used a computerized database that identifies groups of pipes with a high probability of deficiencies. They based their decisions on a traditional engineering evaluation that considers maintenance cost history, soil conditions, street conditions, hydraulic capacity, water quality, and potential for liability.

Stach\textsuperscript{7} of the Dallas (Texas) Water Utility gave similar guidance on pipe replacement. He noted that safety and customer relations are important subjective factors, and attempted to quantify the

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**Literature Review**

Most of the pertinent literature contains qualitative discussions on maintenance of distribution systems but offers little quantitative information on costs of repairs and replacement.

The AWWA Task Group 2850-D\textsuperscript{1} published a committee report on the replacement of water distribution mains. This report indicated which parameters might dictate the replacement of a pipe (e.g., inadequate capacity, adverse effect on water quality, structural inadequacy, greater-than-permissible leakage) and suggested that a useful tool might be a system of reporting repairs and the associated cost of such repairs, thereby enabling a comparison to be made between repair costs and replacement costs. The report does not explicitly answer the question of when to replace pipe.

Shanir and Howard\textsuperscript{2} developed a forecasting technique that uses the number of breaks in a year to predict the optimal year in which a pipe should be replaced. Since their article focused on developing an analytical approach and a sensitivity analysis, they gave very little attention to providing data on the cost of main breaks and estimating the parameters of their break model. So, even though their approach serves as a basis for the work presented in this paper, a considerable effort to collect additional data and several modifications were required to convert their approach into a tool for practicing engineers.

In Great Britain the Standing Committee on Water and Sewer Mains has reported life expectancies of pipelines ranging from 40 to 100 years for calculating depreciation and from 80 to 120 years as accepted normal life for calculating benefits.\textsuperscript{3} However, these values do not necessarily represent the most economical years in which to replace pipe.

A report prepared by the New York District Corps of Engineers\textsuperscript{4} on the underground water distribution facilities in Manhattan contains an excellent general discussion on causes and types of main breaks in cast iron pipes. Some of the causes for breaks are soil movement, impact, contact with other structures, temperature, corrosion, improper laying, and various combinations of all of the preceding. The report contained a table taken from an earlier study of breaks in New York\textsuperscript{5} that showed the wide variation in break rates between cities. The rates varied from 2.07 breaks/km/year (1.29 breaks/mi/year) in Houston, Texas, to 1.62 breaks/km/year (0.912 breaks/mi/year) in Seattle, Wash. Binghamton's rate of 0.17 breaks/km/year (0.11 breaks/ mi/year) over the last decade would rank the city roughly in the middle of the 15 major cities surveyed.

The Manhattan study team\textsuperscript{6} found that the mains were not wearing out with age. The age of the pipe was only a minor consideration in the main replacement program that was developed in the report. The report showed that location and prior
Cost of interruptions by assigning an inconvenience value based on the number of interruptions resulting from pipe failures per year.

**Cost to repair and replace pipes**

It was necessary to be able to predict the costs of repairing or replacing water mains to develop an economical management strategy for maintaining the Binghamton distribution system. Data on the cost of new pipe are easy to obtain, but the pipe repair costs are not generally available in the literature. Shamsi and Howard in 1981 used a replacement cost of $164/m ($50/ft) and a repair cost of $1000/break. These values do not account for the fact that cost varies as a function of pipe size. The following sections give the development of cost functions for Binghamton. Costs are given in June 1980 dollars.

The city of Binghamton uses ductile iron pipe to replace mains. The WES maintains a computer program, Methodology for Arcwide Planning Studies (MAPS), that can calculate costs for various pipe sizes given such information as depth of cover, type of pipe, and diameter or flow. The program was used to generate costs of ductile iron pipe with 1.5 m (5 ft) of cover. The results are presented in Table 1.

Pipe repair costs are not available from standard sources and therefore had to be synthesized. These costs were generated with assistance from the Binghamton water distribution department personnel. The cost to repair a main break can be divided into several items:

- **Cost of Repair = Crew +** Equipment + Sleeve + Repaving + Overhead  \[ (1) \]

The cost of each of these items can be estimated separately (Table 2). The cost for the crew is the sum of the labor cost for a three-man crew, plus the cost of a truck for the crew. These costs were estimated at $27/hour. The number of hours depends on many factors, including pipe size, since it takes longer to shut down the system after a large main break. The time to shut down and repair a break can be given by:

- **Time = 6.5 Diameter \[ ^{2} \text{in.} \]  \[ (2) \]

where diameter is in inches and time is in hours.

The cost for equipment (compressor and backhoe) varies only slightly with the size of the pipe. A cost of $45 is used for all diameters. Breaks are generally repaired by placing a sleeve around the break. The cost of these sleeves varies depending on their length and the thickness as well as the diameter of the pipe. The costs in Table 2 are based on 300-mm (12-in.) long sleeves for diameters of 300 mm (12 in.) and less, and 400-mm (16-in.) long sleeves for diameters greater than 300 mm (12 in.). It is assumed the sleeves would be the type for older (thick) cast iron pipe.

The cost of repairing is based on a unit price of $5.56/m² ($2.00/sq ft) and a 3.6-m (12-ft) long trench. A 1.5-m (5-ft) wide trench is used for 250-mm (16-in.) and smaller pipes. A 1.8-m (6-ft) wide trench is used for 300-450-mm (12-18-in.) pipes, and a 2.4-m (8-ft) wide trench is used for 500-600-mm (20-24-in.) pipes. An additional 20 percent is added to the cost of repair to cover supervision and contingencies. The total costs were verified in a telephone conversation with city of Binghamton personnel.

### Other costs

The costs presented in Tables 1 and 2 refer only to the actual repair or replacement costs. There are other external costs such as inconvenience caused by loss of service or recreation in the street, loss of water as a result of leaks, icy conditions resulting from leaks reaching the road surface, loss of pressure for firefighting during a break, possible contamination of water during repair, and possible subsidence at a break site. In general, consideration of these costs would increase the cost of a break but it is virtually impossible to estimate these costs accurately.

Claims for damage and other inconveniences caused by breaks can be significant in comparison to the cost of actually repairing a break. To account for these other costs, a damage and other cost multiplier factor \( D \) will be introduced. The cost of a break \( C_b \) will be the cost given in Table 2 (\( C_{b0} \)) times this factor.

\[
C_b = C_{b0} D \tag{3}
\]

where \( D \) is the damage and other cost multiplier; \( C_{b0} \) is the overall cost of the break—$/break; and \( C_{b} \) is the cost to repair the break—$/break (Table 2). When these other costs are ignored, \( C_{b0} = C_{b} \) and \( D = 1 \). When these other costs are significant (e.g., 150 percent of repair cost), \( D \) will increase (\( D = 2.5 \)).

### Determining significant parameters

There were three types of pipe in the Binghamton distribution system—pit cast iron, sandspun cast iron, and ductile iron. The first two types had been in use for many years and 398 and 112 breaks were reported, respectively. The ductile iron pipe had only a handful of breaks, not enough on which to base a predictive function. There was also only 1.67 km
coefficients \(a, b\) for each size, previous break history, and type of pipe. Unfortunately, there were not enough observations of breaks to arrive at this large number of coefficients. There were two different aging rates for pipes depending on the material [pit and sandspun cast iron]; therefore, two regression equations were developed.

Because the break rate varied greatly from one year to the next as a result of factors such as the severity of the winter, the break rate data were grouped into five-year increments for the regression analysis in order to smooth out the annual variations. Pipes that had been replaced were not included in the analysis. The regression equations developed are:

**Pit cast iron**

\[
N(t) = 0.02577 e^{0.3073(t)}
\]  
(5a)

**Sandspun cast iron**

\[
N(t) = 0.0627 e^{0.1273(t)}
\]  
(5b)

The values for \(b\) in Eq 5 are comparable to the range of values for \(b\) of 0.01–0.15 as determined by Shamir and Howard\(^2\) and of 0.08 as measured by Clark.\(^*\) The fact that the values for \(b\) in Eq 5 are on the low end of the range indicates that the break rate does not increase rapidly with age. This suggests that the soils in the study area are not highly corrosive, a hypothesis that was verified by using the SCS Soil Survey for Broome County, N.Y.\(^5\)

Equation 5 serves as the basis for the break prediction model but does not account for the higher break rates of pipes with previous breaks and of large pit cast iron pipes. Correction factors for these cases follow.

**Previous break factor.** A cursory examination of the data indicated that once a pipe broke it was more likely to break again. This was verified by the analysis-of-variance test. Since there were not enough data to develop individual cost functions [i.e., as and \(bs\)] for pipes with previous breaks, a correction factor \(c_x\) was developed to modify the overall predicted break frequency for a specific type of pipe. The form of the correction factor is

\[
c_x = \frac{\text{Break frequency for } \text{pit/sandspun cast iron with no/one or more previous breaks}}{\text{Overall break frequency for } \text{pit/sandspun cast iron}}
\]

(6)

The data used to calculate \(c_x\) are given in Table 3 and the values for \(c_x\) are given in Table 4.

**Pipe-size factor.** Since large, pit cast iron pipe exhibited a significantly higher break frequency than smaller pipe, another correction factor \(c_x\) was required to modify the overall predicted break frequency for pit cast iron pipe to account
set for break rate versus temperature and age. The best-fit equation is

$$N(t, T) = 0.0107 e^{0.0125(T - T_0)}$$  \(\text{(8)}\)

where \(T\) is the average temperature in the coldest month. When the average value of \(T\) for the study period is inserted in Eq 8, it reduces to

$$N(t) = 0.1350 e^{0.0125(t - t_0)}$$  \(\text{(9)}\)

which is reasonably close to Eq 5a. A regression of break rate and average temperature in the coldest month yields

$$N(t) = 0.1700 e^{0.0125(t - t_0)}$$  \(\text{(10)}\)

The above analysis indicates that the temperature in the coldest month is significant in predicting the break rate. While the effect of frost penetration can be included in an analysis of historic break data, it cannot be used in predicting breaks since it is impossible to predict the severity of a winter before the fact. So, Eq 5 must be used for developing replacement guidelines instead of Eq 8.

**Summary of prediction model.** The pipe break prediction model to be used in the remainder of this study is

$$N(t) = c_2 \cdot c_3 \cdot e^{0.0125(t - t_0)}$$  \(\text{(11)}\)

where \(N(t)\) is the break rate for year \(t\)—breaks/year/mi; \(c_2\) is the correction factor for previous breaks (see Table 4); \(c_3\) is the correction factor for size (see Table 6); \(a\) is the regression coefficient—breaks/year/mi (0.02577 for pit cast iron and 0.0627 for sandspun cast iron); \(b\) is the regression coefficient (0.0307 for pit cast iron and 0.0137 for sandspun cast iron), and \(k\) is the year of pipe installation.

**Maintenance requirements.**

The pipe break prediction model developed above can be used to predict the cost of repairing the breaks in the future. For each of the next 20 years, the expected value of the cost to repair a break was calculated on the basis of pipe material, length, diameter, and previous break history. The sum of the costs in 1980 dollars is given in Table 7, which shows that as the system ages, the pipe break rate and break repair costs will steadily increase. If the value of \(b\) is 0.02, and if inflation is ignored, the costs will double every 34.5 years. If inflation is considered, the doubling time will be greatly reduced.

Table 7 is based on winters of average frost penetration. The actual cost in future years will depend highly on the severity of the winter. For example, the cost in 1985 is predicted to be $95,900 based on the coldest average monthly temperature of \(-6^\circ\text{C}\) [21.2°F]. If the coldest month in a winter were to be \(-11.4^\circ\text{C}\) [11.4°F] (as in 1934), the costs would rise to $131,000.
TABLE 7
Projected cost to repair breaks

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost 2908 $</th>
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<tbody>
<tr>
<td>1961</td>
<td>98 500</td>
</tr>
<tr>
<td>1962</td>
<td>90 000</td>
</tr>
<tr>
<td>1963</td>
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<tr>
<td>1969</td>
<td>103 000</td>
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<td>1970</td>
<td>105 000</td>
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TABLE 8
Critical break rate

<table>
<thead>
<tr>
<th>Pipe Diameter</th>
<th>D/L = 1</th>
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<th>D/L = 5</th>
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<td>1.72</td>
</tr>
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<td>180 000</td>
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<td>3.41</td>
<td>2.7</td>
<td>1.72</td>
<td>2.7</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Optimal replacement age

Once the cost of repairing pipes is known, the next question to be answered is what pipe should be replaced and when it should be replaced. A rule developed by Shamir and Howard for determining the optimal age at which a pipe should be replaced is:

\[ t^* = k \ln \left[ \frac{L, C, 5208 \ln (1 + R)}{C, a, c, c} \right] \]  \hspace{1cm} (12)

where \( a \) is the regression coefficient in Eq 11—break/year/mi; \( b \) is the regression coefficient in Equation 11—one/year; \( c \) is the correction factor for previous breaks; \( e \) is the correction factor for large pit cast iron pipe; \( C \) is the cost of a break—$/break; \( C_r \) is the cost to replace pipe—$/ft; \( R \) is the year of pipe installation; \( L \) is the fraction of pipe to be replaced (ratio of length replaced to total length); \( R \) is the interest rate; and \( t^* \) is the optimal year to replace pipe—years.

The value of \( t^* \) was calculated for all of the pipes in the system. This was done for \( L = 1, R = 7-1/4, C_r, C \), and \( C \), as given in Tables 1 and 2 (with \( D = 1 \)) and \( a, b, c, c \), and \( k \) as appropriate for that pipe. None of the pipes need replacement at present.

The sensitivity analysis of Eq 12 indicated that the optimal replacement year \( t^* \) was highly dependent on \( b \) (i.e., the rate at which the pipes age). Since \( b \) was found to be generally about 0.02, Eq 12 shows that it is not economical to replace either type of pipe before it is at least 100 years old even if it has experienced previous breaks.

The pipe segments used in the analysis are generally several hundred metres (feet) long. So, while Eq 12 shows that it is not generally economical to replace entire pipes, it may still be economical to replace sections of the pipe that have experienced a number of breaks. Ductile iron pipe comes in 5.4- and 6.0-m (18- and 20-ft) laying lengths, so it may be economical to replace several bad lengths of pipe in an overall sound pipe. The parameter \( L \) in Eq 12 is the ratio of the length replaced to the total pipe length. As the length replaced decreases, the optimal replacement time increment (i.e., age of pipe at replacement) decreases. For example, if 27 m (90 ft) of a 225-mm (900-ft) pipe segment to be replaced, the optimal replacement age may decrease from 210 to 95 years. Theoretically, in the case of pipes with previous breaks, their optimal age at replacement may be decreased until it becomes optimal to replace the pipe today. System maintenance costs can be decreased if bad sections of pipe are identified and replaced. Unfortunately for this study, the data were only available on the basis of large segments (several hundred metres (feet)) so it was impossible to identify where replacing short sections could be economical. The unit price of replacement pipe is larger for small jobs so the prices in Table 2 should be increased accordingly.

Identification of bad pipes

The criterion given for pipe replacement in Eq 12 is for pipes with typical values of \( a \) and \( b \). It shows that it is not generally economical to replace these typical pipes at present unless only small portions of the pipe are replaced. Nevertheless, there are some pipes that have significantly higher break rates (i.e., \( a \) and \( b \) from Eq 11 are low for these pipes) as a result of bad laying conditions, contact with structures, impact or unusually heavy frost or truck loads.

A criterion to identify these bad pipes is developed in Appendix A. It states that if a pipe's current break rate \( F \) is greater than some critical break rate \( F^* \), it should be replaced. This criterion can be given as:

\[ \frac{C, 5208 \ln (1 + R)}{L} \ln \left( \frac{e^R}{1 + R} \right) = \frac{F \ln (1 + R)}{L} \ln \left( \frac{e^R}{1 + R} \right) \]  \hspace{1cm} (13)

where \( F \) is the current break rate—breaks/year/mi; \( F^* \) is the critical break rate—break/year/mile; \( C_r \) is the cost to replace pipe—$/ft; \( C_r = DC \), is the cost of break—$/break; \( L \) is the fraction of pipe replaced; \( b \) is the regression coefficient—one/year; \( R \) is the interest rate; and \( m \) is the period of analysis—years.

Values for \( F^* \) depend on the diameter of the pipe, the amount of damage, and other costs of a break (\( D \) in Eq 10); the period of analysis (\( m \)); the amount of pipe to be replaced (\( L \)); the rate of increase of breaks (\( b \)); and the interest rate (\( R \)). Value of \( F^* \) are shown in Table 8. For large values of \( m > 50 \), \( F^* \) is insensitive to \( m \) for large \( m \) since \( e^R < 1 + R \); therefore, \( m = \infty \) is used:

\[ \left( \frac{e^R}{1 + R} \right)^{1/2} \]  \hspace{1cm} (14)

Also, for Table 8, \( R = 7-1/4 \) percent, and \( C_r \) and \( C \) are taken from Tables 1 and 2. Replacing only part of the pipe (i.e., decreasing \( F \)) or including damage and other costs in the break cost (i.e., increasing \( D \)) has the same effect on the critical break rate, so these parameters are lumped together in a dimensionless group (\( D/L \)). The effect of increasing this
The damage factor \( D \) depends on the location of the pipe. In a central city area with subways, buried utilities, and deep basements, \( D \) can be as high as 10, while in a rural area the damage caused by a break may be negligible \( (D = 1) \). The value of \( D \) is a judgment decision based on location. In some cases it may be better to use several values for \( D \) (e.g., 5 in downtown, 2 in commercial and residential areas, and 1 in rural areas for cross-country pipelines).

The value of \( B \) is based on the interest rate and is a value set by the policy of the utility. (Note that an interest rate of, say 7 percent, is inserted in Eq 13 as 0.07 and not 0.7.)

The value of the fraction of pipe replaced depends on the ability of the utility to locate accurately and replace the bad portion of the pipe segment. A value of 0.5-0.2 can be used to account for this. In general, as the length of a segment being considered increases, the value of \( L \) should decrease.

The most difficult variables to evaluate are \( B \), the rate at which pipe breaks increase with age, and \( m \), the period of analysis. In Appendix A, it is shown that \( m \) is only important where \( b > \ln (1 + R) \), and the replacement pipe will have the same value of \( b \) as the original pipe. This is not true in most cases, and \( m \) can be set to any large number. There are several different possibilities that can occur:

- \( b > \ln (1 + R) \) In this case, \( m \) is important since the rate at which breaks increase with age is greater than the decrease in the present worth of replacement with time. The break rate of the replacement pipe must be considered as shown in Eq A5. This is generally not the case.

The value of \( J^* \) for a given category [i.e., size, type] of pipe depends on the following parameters from the definition of \( J^* \) in Eq 13; the cost to repair a break \( (C) \), the cost to replace a pipe \( (C_r) \), the damage factor \( (D) \), the portion of the pipe replaced \( (L) \), the interest rate \( (R) \), the rate of change of breaks with time \( (b) \), and period of analysis \( (m) \). The subsequent paragraphs describe how to determine each of these parameters.

The costs of repairing and replacing pipe should be determined for each individual utility, based on local prices and local experience. Typical costs are given in Tables 1 and 2. Those costs are a function of diameter so a separate \( J^* \) is required for each diameter unless the ratio of \( C_r/C \) is essentially constant. If the ratio is relatively constant, then a single \( J^* \) is possible for all diameters.

The period of time for which break data are available should be fairly long if \( b \) is to be a good indicator of pipe aging and not affected by other variables (e.g., weather).

**Summary**

There are essentially two approaches that can be used to apply these methods to a real distribution system. The approach given in Eq 12 is useful for deciding whether to replace entire groups or to determine when a pipe should be replaced. Equation 12 generally indicates that no pipes need to be replaced, since the good pipes in a given category tend to compensate for the bad ones. The method developed in Appendix A as given in Eq 13 is useful in analyzing the economics of replacement on a pipe-by-pipe basis. For many cases, Eq 13 can be simplified to Eq 15 and Eq 16. Its use is recommended instead of Eq 12.

Pipes break as a result of many factors, including improper laying, impact, contact with other structures, frost loads, soil movement, corrosion, freezing, and various combinations of such occurrences. A set of equations is developed in the report to predict the rate of breaks of pipes depending on their diameter, age, materials, temperature, and previous break history. Although the equations describe the break rate for typical pipes, there is considerable variation among pipes.

Given typical labor and equipment requirements, data are synthesized to predict the cost of repairing a break as a function of pipe diameter. The true cost of a break should also include an estimate of damage and inconvenience. Based on an economic analysis, it is possible to predict when typical pipes should be replaced. With a similar analysis, it is possible to identify pipes that need immediate replacement.

The decisions of whether and when to replace a pipe depend on the cost of a break \( (C_r) \), the price of replacement pipe \( (C) \), the total length of the pipe \( (l) \), the length of pipe to be replaced \( (l_r) \), the pipe diameter \( (c) \), the previous break history \( (C) \), interest rate \( (R) \), the type of pipe \( (b) \), and the rate at which the pipe is aging \( (b) \). The decision to replace pipe is most sensitive to changes in \( l/l_r \) and \( b \).

**Appendix A**

Development of criteria to identify bad pipes. In Binghamton it is generally not economical to replace typical pipes in the system. Nevertheless, it will be economical to replace all or part of some pipes that have had a record of numerous breaks. A rule to identify those pipes based on their present break rate is given here. This rule can be derived by comparing the cost of breaks based on the current break rate \( r \) (current year is \( l \)), with the cost of replacing the pipes. The pipe should be replaced if...

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replaced if the present worth of the cost of repairing the breaks between year \( j \) and \( j + m \) is greater than the replacement cost. This can be written as

\[
P_r = \int_{j}^{j+m} \frac{C_{J}\text{e}^{\alpha t}}{(1 + R)^t} dt > I, C, 5280 \quad \text{(A1)}
\]

where \( I \) is the break rate in year \( j \)—break/year/mi; \( m \) is the period of analysis—years; and \( P_r \) is the present worth of breaks—dollars. The left side of Eq A1 can be simplified to

\[
P_r = I \frac{C_J}{(1 + R)^j} \int_{j}^{j+m} \left( \frac{\text{e}^\alpha}{1 + R} \right)^t dt > I, C, 5280 \quad \text{(A2)}
\]

Equation A2 can be integrated to give

\[
P_r = I J \frac{C_J}{(1 + R)^j} \left[ \left( \frac{\text{e}^\alpha}{1 + R} \right)^{j+m} - 1 \right] \quad \text{(A3)}
\]

The relationship given in Eq A4 can be used to identify the pipes that need immediate replacement.

In Eq A4 for \( \text{e}^\alpha/(1 + R) < 1 \) [i.e., \( b < \ln (1 + R) \)], \( \text{e}^\alpha/(1 + R)^n \) will approach zero for large \( n \). This is the case in which \( b > \ln (1 + R) \), \( m \) becomes important because the rate of increase in costs resulting from the increase in the rate of pipe breaks is greater than the rate of decrease in the present worth of costs as a result of interest. In this case, \( m \) will tend to be small and the break rate of the new (i.e., replacement) pipe must also be considered. Equation A1 then becomes

\[
P_r = I \int_{j}^{j+m} \frac{C_J \text{e}^{\alpha t}}{(1 + R)^t} dt > I, C, 5280 + \left\{ \text{Cost of repair and eventual replacement of the new pipe} \right\} \quad \text{(A5)}
\]

Equation A5 becomes especially complicated if the new pipe is different from the old pipe because its break rate is not known. This is true in many cases because the new pipe may be of better quality, with better installation or added protection against freezing, expansive soils, and corrosion. In Binghamton, it was found that \( b < \ln (1 + R) \), so Eq A4 was appropriate for the study.

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References


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