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Organizing and analyzing leak and break data for making main replacement decisions

D. Kelly O'Day

Water main replacement decisions may be based on arbitrary criteria such as age or on historic operating records and the experiences of a utility. Use of the latter method enables a utility to analyze leak and break patterns and to develop rehabilitation-replacement plans. The author provides an overview of the causes of water main breaks and leaks and then describes several studies in which water main breaks have been analyzed in terms of pipe age, geographic location, or diameter.

Managing water distribution systems requires careful attention to capacity, finance, maintenance, and water quality. Many managers of older urban systems are faced with high unaccounted-for water losses, structural deterioration of mains, and limited funds with which to maintain and rehabilitate these aging distribution systems.

This paper presents examples of how analysis of routine operating records can be used by managers to help pinpoint problem mains so that actions can be taken for maintenance-rehabilitation. This paper stresses the concept of pinpointing the problem mains so that only the specific main sections causing problems are rehabilitated. This approach is less costly than the more general approach of rehabilitating mains based in age or some other general criterion.

Main leaks and breaks

Leaks occur when either joints or service connections are not tight; breaks occur when a main fractures. This distinction may be overlooked because individuals often classify leaks and breaks according to the quantity of water being discharged. Thus, a bell crack may be called a leak if the discharge is small. This semantic problem is further compounded by the term "leakage survey," which includes water loss from both leaks and joint leaks.

The distinction between breaks and leaks is important for understanding problems and causes within the system and for comparing experiences between systems. In order to accurately assess the structural integrity of lines, one must separate main breaks that represent structural failures from joint leaks that represent inadequate joint sealing. From a 1980 report to Congress, Table 1 shows a comparison of reported main break rates for 15 large water systems in the United States. Break rates vary from 36 to 1290 breaks/1000 km/1000 mil of main/year. This diversity in break rates is highly misleading because there are no consistent definitions for leaks and breaks. For example, some systems (New York City) report only main breaks whereas others (Houston) report leaks and breaks.

Causes of water main breaks

A detailed discussion of what causes main breaks is beyond the scope of this paper; however, a general explanation of the varied causes is helpful. The principal reported causes of main breaks can be divided into three categories—excessive load, temperature, and corrosion.

Excessive loads. Mains are designed to withstand anticipated internal and external forces. However, structural failure can occur if the actual forces exceed the structural strength of the pipe material owing to poor design, deterioration of pipe strength, or unanticipated forces. For purposes of this discussion, it is assumed that the pipe has been designed properly. Deterioration can occur through corrosion, which will be discussed later. Unanticipated forces that exceed the pipe’s strength can occur from excessive internal pressure, which causes hoop stress failure; excessive external load, which causes ring failure or crushing; or inadequate bedding support, which leads to beam failure.

Small-diameter mains (150-200 mm [6-8 in.] ) often experience beam failure because of poor bedding conditions, but ring or crushing failure in these mains is very unlikely. Large mains (2250 mm [89 in.] ) are likely to experience ring failure or crushing and unlikely to experience beam failure. Beam failure causes a complete circumferential break, whereas crushing loads cause longitudinal breaks. Excessive hoop stress causes blowout of the weakest portion of the main wall.

Beam failure in small mains can be caused by poor initial construction, erosion of the bedding by joint leakage, soil movement from the shrink–swell of expansive soils, and soil shifting caused by adjacent construction. Crushing loads can be caused by truck traffic or by excessive loads from the effects of frost penetration.

Temperature. Water systems in the northern sections of the United States experience a major (60–70 percent) portion of the annual main breaks in the four winter months of November–February. The lower temperatures in these months affect mains in two distinct ways: (1) increased tensile stress on mains is caused by temperature-induced contraction, and (2)
increased external stresses are caused by soil-moisture expansion from frost penetration.

Temperature-induced contraction does not cause excessive stresses because of the flexible bell-spigot joint. However, structures in contact with the main may restrict contraction, creating excessive tensile stresses. Frost penetration forces may cause main breaks in situations where the bedding has been disturbed, causing a beam failure. Experiences in many northern cities indicate a substantial increase in small-main breaks in severe winters. These probably are caused by a combination of either poor bedding conditions or active corrosion and excessive loads from frost penetration of the covering soil.

**Corrosion.**Corrosion of cast iron mains is the electrochemical reaction (graphitization) between the pipe metal and its environment; the pipe loses its ferritic constituent, leaving behind the graphite. The two major sources of corrosion are galvanic reaction between the pipe and its surrounding soil and stray direct electric current. The literature reflects a diversity of opinion regarding the relationship between corrosion and main breaks. Fitzgerald states: "It has been recognized, however, by water utility personnel that the majority of the breaks occur at locations where the pipe wall has been weakened. Such weakening is the result of graphitic corrosion of cast iron and, although the actual failure may be due to stress, corrosion can be shown to be the real cause."

This opinion can be contrasted with statements in the General Accounting Office's report to Congress:

External corrosion of cast iron mains does not appear to be a major problem...

According to the Cast Iron Pipe Research Association, most of the soil in the United States is not corrosive to cast iron pipe. A survey by this association in 1970 showed that only 5 percent of 121,500 miles of pipe in 229 cities in 48 states was affected by corrosion. Pipe age ranged from new to 149 years old. An earlier survey, in 1969, by the American Standards Association (now the USA Standards Institute) disclosed that 83,000 miles of cast iron main installed by 110 utilities, less than 2 percent was in areas where serious corrosion had been encountered.

Clearly, there is a wide difference of opinion about the significance of corrosion in cast iron mains.

The National Bureau of Standards has conducted extensive corrosion research, including field tests started in 1922 to determine the corrosion rates of commercially produced ferrous pipe materials in soil environments. Gerhold published results from corrosion rate studies started in 1958 for ductile cast iron pipe material in six soil types. The results for 14 years of this study are summarized in Table 2. The observed corrosion is reported in terms of the measured weight loss and the maximum pit depth.

A review of the data in Table 2 shows that there is a consistent pattern of weight loss and pit depth increase over 14 years. However, the rates of weight loss and pit depth increase vary substantially from soil type to soil type. For example, the clay soil samples had a weight loss of 4.2 kg/m² (13.8 oz/sq ft) in 8 years, whereas the sandy loam sample had a weight loss of only 1.5 kg/m² (4.9 oz/sq ft) in 14 years. Moreover, the clay samples had complete perforation in 4 years, indicating a pit depth of 3.5 mm (250 mil), whereas the sand sample had only a 1.2-mm (79-mil) pit depth in 14 years.

The data for sample A illustrate an interesting example of variations in pit depth within the same soil type. The specimen removed for the 8-year analysis had complete perforation, indicating a 6.35-mm (250-mil) pit depth. The 14-year specimen had only a 2.2-mm (88-mil) pit depth. These two specimens were exposed to similar soils, yet the 8-year specimen had a pit depth that was almost three times that of the 14-year specimen. These results clearly indicate the variability between soil types and significant variations within a single soil.

Some soils, such as clays and highly organic soils, can be highly corrosive. Fortunately, highly corrosive soils are geographically limited in the United States. However, corrosive conditions can exist in noncorrosive soils. Mixing sand and clay backfill material can create a galvanic reaction that will slowly corrode a cast iron main. In many utilities, corrosion occurs and may explain a high proportion of the main breaks. Morris reported on main break experiences in several Texas cities. Dallas had 3899 breaks in the period 1960–1965. Bluwouts, which indicate intensive corrosive action, accounted for 32.5 percent of the breaks. Morris estimated that an additional 27 percent of the breaks could be considered corrosion-induced, making 59.7 percent of main breaks attributable to corrosion. In Fort Worth an estimated 30 percent of the main breaks were corrosion-induced. In Corpus Christi, 50 percent of the breaks were associated with soil electrolysis (corrosion), and 50 percent were related to soil movement. All these cities have extensive clay soils, which clearly affect corrosion activity.

Corrosive soils cause high rates of graphitization, whereas noncorrosive soils can have low rates of graphitization that will not cause significant metal loss for 80–150 years. In addition, stray direct electric current can be a problem in urban areas with mass transit systems.

All main breaks should be reviewed carefully to determine whether the cause was excessive forces, temperature, or corrosion, or possibly a combination of these factors.

**Effect of age on main breaks**

There has been a growing concern that many older urban water distribution systems are deteriorating and in need of massive rehabilitation. Many studies predict that rehabilitation programs costing billions of dollars will be required to replace mains older than some predetermined number of years in age or "useful life." The useful life for water mains has been reported by others to be between 60 and 100 years. However, the author has found no scientifically based criteria for defining a water main's useful life.

Several studies have evaluated age as an indicator for predicting the break rate for cast iron mains. In a study of main breaks in Binghamton, N.Y., the U.S. Army Corps of Engineers evaluated the correlation between main age and average break rate for both pit cast and sand spilt cast iron mains. Figure 1 is a plot of graph versus break rate for both types of cast iron main. The following equation was used to determine the relationship between age and break rate:

\[ y = \frac{k}{x + \text{constant}} \]

Where:
- \( y \) is the break rate (breaks per mile per year)
- \( x \) is the age of the main
- \( k \) is a constant value
- \( \text{constant} \) is another constant value

The equation was found to have a high degree of correlation with the data collected.
TABLE 1  
Comparison* of water main break rates in 15 US cities

<table>
<thead>
<tr>
<th>City</th>
<th>Year Reported</th>
<th>System Length</th>
<th>Main Breaks Per Year</th>
<th>Main Breaks and Joint Leaks Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mi</td>
<td>km</td>
<td>Number</td>
</tr>
<tr>
<td>Boston</td>
<td>1968-78</td>
<td>1060.0</td>
<td>1740</td>
<td>39</td>
</tr>
<tr>
<td>Chicago</td>
<td>1973</td>
<td>4144.0</td>
<td>6670</td>
<td>223</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>1968-78</td>
<td>2890.0</td>
<td>4670</td>
<td>289</td>
</tr>
<tr>
<td>Denver</td>
<td>1978</td>
<td>1790.0</td>
<td>2890</td>
<td>289</td>
</tr>
<tr>
<td>Houston</td>
<td>1973</td>
<td>3800.0</td>
<td>6050</td>
<td>222</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>1969-78</td>
<td>2890.0</td>
<td>4670</td>
<td>289</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>1974-77</td>
<td>19900.0</td>
<td>31900</td>
<td>1990</td>
</tr>
<tr>
<td>Louisville, Ky.</td>
<td>1968-79</td>
<td>2290.0</td>
<td>3670</td>
<td>167</td>
</tr>
<tr>
<td>Milwaukee</td>
<td>1973</td>
<td>1800.0</td>
<td>2910</td>
<td>290</td>
</tr>
<tr>
<td>New Orleans</td>
<td>1969-78</td>
<td>7600.0</td>
<td>12200</td>
<td>412</td>
</tr>
<tr>
<td>New York City</td>
<td>1976</td>
<td>1176.0</td>
<td>1900</td>
<td>104</td>
</tr>
<tr>
<td>San Francisco</td>
<td>1973</td>
<td>1373.0</td>
<td>2210</td>
<td>106</td>
</tr>
<tr>
<td>St. Louis</td>
<td>1969-78</td>
<td>1250.0</td>
<td>2000</td>
<td>25</td>
</tr>
<tr>
<td>Troy, N.Y.</td>
<td>1969-78</td>
<td>1406.0</td>
<td>2260</td>
<td>163</td>
</tr>
</tbody>
</table>

*Variations in reporting conventions for leaks and breaks by water utilities limit the usefulness of this comparison. It is likely that the differences between cities are both definitional and real.

TABLE 2  
Ductile iron corrosion rates

<table>
<thead>
<tr>
<th>Years in Ground</th>
<th>Weight Loss</th>
<th>Pit Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/m</td>
<td>oz/sq ft</td>
</tr>
<tr>
<td>Sample*</td>
<td>Soil</td>
<td></td>
</tr>
<tr>
<td>A Sandy</td>
<td>loam</td>
<td>0.1</td>
</tr>
<tr>
<td>B Flint</td>
<td>loam</td>
<td>0.4</td>
</tr>
<tr>
<td>C Clay</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>D Sand</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>E Sand</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>F Clay</td>
<td>0.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*The size of the original specimen was 305 mm x 63.5 mm O.D. x 0.35-mm wall thickness. (12 in. x 2.5-in. O.D. x 0.025-in.)

**P** perforation

Sample E was lost; therefore measurements are not available for years 4, 8, and 14.

Iron mains. The coefficients of determination (R²) were 0.574 and 0.162, respectively, for pit cast and sand spun mains. These results indicate that age alone is a poor indicator of main break patterns.

It is interesting to note that the sand spun mains had a significantly higher break rate than the pit cast mains even though the sand spun mains were much newer. The early manufacturing of sand spun mains was not as good a process as the older pit cast techniques.

The Binghamton study found that the previous break history of a pipe made a significant difference in the probability of a future break. In Table 3, the break rates for mains with no previous history are compared with those for mains with one or more previous breaks.

For both sand spun and pit cast mains, the break rate for mains with a previous history of breaks was an order of magnitude greater than that for those mains with no previous history of breaks. Thus, 25 percent of the sand spun mains and 17 percent of the pit cast mains had break rates 13.7 and 11.25 times the break rate for mains with no previous history. This indicates that once a main segment starts to break, its break rate will be much higher than that for the overall system. A rehabilitation program should solve the problems in the 3-5 percent of the system where major breaks occur.

In a study of Severn-Trent Water Authority's [England] experience with main breaks, Newport reported that "age is not a good indicator of condition." In comparing break rates for various sections of the distribution system, he found that spun cast iron installed since 1952 had break rates much higher than mains installed from 1890 to 1920.

In an analysis of water main breaks in Manhattan, New York City, with the author found age to be unsuitable for predicting main break rates. Figure 2 presents the break rates by diameter for mains 5 to 125 years old. There is no clear pattern of increasing break rates with age; in fact, some newer pipe has break rates higher than older pipe.

In a study of external corrosion of cast iron gas mains, the Ontario Research Foundation reported that "...cast iron mains in Metropolitan Toronto soil will have a very long mean life in the order of 700 years."

These studies show that age is not the major determinant of water main break rates. Rather, highly localized factors—corrosion conditions, construction practices, and external loads—determine the actual break rate. Systems with high soil corrosivity and existing main breaks exhibit high break rates, even for new mains. Therefore, it is essential to identify and contain the corrosion problems.

Geography of main breaks

The causes of main breaks vary widely from utility to utility and within a single utility. Geographic analysis of break and leak patterns can be helpful in understanding causes and in developing solutions. The following paragraphs present examples of geographic analyses of main breaks: in Severn-Trent, England, and New York City.

Severn-Trent, England. Newport has...
reported on his analysis of main breaks in six areas of Nottingham, England, for the period 1970–77. His data are presented in Table 4. This analysis indicates a very wide range of break rates, ranging from 0.129 to 0.628 breaks/1.6 km (1 mi)/year. Newport reported that in the areas where breaks occurred most frequently, the mains were all sand and spun iron and had been installed since 1932. Thus, this geographic analysis pinpointed the break problem more clearly and confirmed that the method of pipe manufacture, not age, was the significant factor.

Newport also analyzed break rates by soil type, as presented in Figure 3. This geographic analysis indicates that the relative break rate varies from 1.5 for clays to 0.65 for river gravels. The soil type has a significant influence on break rates because it affects the external forces on the main (shrink–swell and frost penetration) and external corrosion.

New York City. The New York District of the US Army Corps of Engineers conducted a study of main breaks in Manhattan. 8,10 This study included an analysis of break trends throughout the city and an in-depth geographic analysis of 2308 main breaks that occurred in Manhattan’s 1120 km (695 mi) of water main from 1955 to 1978.

Figure 4 is a comparison of break rate trends in New York City during the period 1959–1975. Manhattan experiences a much higher break rate than the other four boroughs. Table 5 shows this geographic diversity more dramatically by comparing the break rates in 1975 for the four boroughs, overall Manhattan, and Manhattan’s high-break tracts.

The range of break rates across New York City confirms the need for effective geographic analysis of break patterns. In Manhattan, the break rate for 150-mm (6-in.) mains is 3.9 times that in the other four boroughs. Twelve tracts had a break rate twice that of the average break rate for Manhattan or 13.9 times that for the four boroughs.

Computerized geographic analysis of breaks. In conducting a detailed analysis of Manhattan’s breaks, the Corps of Engineers used the US Census Bureau’s geographic base file (GBP/DIME) as a geographic reference system to construct a computerized inventory of the 1120 km (695 mi) of water main. The 2308 main breaks were then cross-referenced to the appropriate mains in the inventory by using the ADMATCH program.* The result of the cross-referencing step was a computer-based history of breaks for all main segments in Manhattan for the period 1955–1978.

An extensive computer analysis of this history file was conducted to understand break patterns in Manhattan and to pinpoint "hot spot" areas.

A series of analyses were performed after the main inventory and 25 years of break history were set in a computer file. The following are brief descriptions of these analyses:

Break rate analysis. A series of cross-tabulations were prepared to compare break rates by age. Figure 2 shows such a comparison.

Break cause analysis. A series of tabulations were prepared to summarize the 2308 break reports. Summaries were made of break type, pipe thickness of broken mains, damages, contact with other structures, duplicate break mains, and reported main corrosion. Table 6 presents a typical tabulation that summarizes breaks in contact with other structures.

Temperature analysis. The break rate...
break patterns in Manhattan, a recommended replacement program for break-prone mains, a computerized history of each main segment (which can be used as an ongoing management tool), and a predictive model that indicates the likelihood of a main breaking.

This study demonstrated the usefulness of a geographically based history in analyzing main break patterns and in developing realistic rehabilitation and replacement plans for actual problem areas.

Information management approach to main rehabilitation

Effective water main maintenance, rehabilitation, and replacement decisions must be based on realistic and up-to-date information on the physical condition of the water distribution system. Use of a computerized information system can provide this critical information if the system: (1) incorporates routine field operations' records for leaks, breaks, pressure tests, and C-values; (2) is geographically oriented so that operating histories can be kept for each main segment; and (3) is designed for use by water utility engineers rather than by data processing personnel.

Choice of a geographic reference system may be simplified by using the US Census Bureau's geographic base file, GBF/DIME, which was developed for 256 metropolitan areas throughout the United States. This file is essentially a computerized street directory with detailed geographic information for every street segment (portion of street between two intersections) in a metropolitan area. This file can be used readily to develop a computer-based inventory of each segment of main in a utility's service area. Thus, all routine operating records can be cross-referenced to the appropriate segments so that complete leak, break, pressure, and C-value histories can be kept for the main.

A geographically based information system can be queried for information on high-break mains or leak-prone mains or high-break, leak-prone, low C-value mains. The utility can replace rule-of-thumb maintenance and rehabilitation judgments with decisions based on actual experience. Why replace a 100-year-old main if it has had few leaks and breaks? Should the utility clean and line or replace an 80-year-old grey cast iron main? Careful analysis of the utility's past experiences will help to determine whether the line is structurally adequate for re-lining or needs to be replaced.

The GBF/DIME file has been used successfully in New York City, Chicago, and Houston to develop water main information systems. If this file is available for a utility's service area it is a powerful geographic reference system because it uses the existing street network, includes address ranges for each street segment.
Breaks occur when a main fractures. The major causes of main breaks are excessive load, temperature, and corrosion.

and has X-Y coordinates for computer mapping purposes.

Once the utility has selected a geographic reference system, it must develop a computer-based main inventory and enter historic operating records into a computer file.

Finally, current record keeping for all field work should be reevaluated to determine whether all potentially valuable information is being recorded. The following questions should be asked: Are the types of breaks recorded? What caused the breaks? Are proper distinctions made between leaks and breaks? Are C-values from trunk main surveys and pressures, and hydrant discharges from fire department tests recorded? The answers to these questions indicate how valuable information about the condition of the distribution system is being used to help make replacement decisions. This information should be properly and systematically recorded and, if appropriate, included in the information system.

Figure 6 presents a suggested design for a geographically based information system.

Conclusions

The cost of replacing a mile of water main is $200,000–$500,000 (in 1980 dollars). In this period of rising costs, shrinking revenues, and high interest rates, main rehabilitation-replacement decisions should be based on sound, reliable information. Arbitrary criteria such as age are unrealistic and costly. If a utility adopts a policy of replacing mains that are more than 100 years old, it may replace many miles of sound, useful mains while failing to replace problem segments that are 30–50 years old.

Replacement decisions should be based on the physical condition of mains, not on their age. A geographically oriented information system will cost $50–$150 per mile to develop and $10–$20 per mile per year to update with routine records. The monetary gain from improved main replacement decisions is several orders of magnitude greater than the cost of the information system.

By organizing and analyzing the distribution system’s existing data, a utility can improve overall distribution management by pinpointing those areas in need of rehabilitation.

Acknowledgment

The author directed the New York City Water Supply Infrastructure Study in his previous position as vice president, Betz, Converse, Murdoch, Inc., Plymouth Meeting, Pa.

References


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