# A REVIEW AND A METHODOLOGY FOR SCHEDULING OPTIMAL REPLACEMENT OF PIPES IN WATER DISTRIBUTION SYSTEMS

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**Abstract**: In this paper a review of various methods of identifying failure prone pipes in water distribution systems is presented. Also a new analytical methodology that separately deals with an economically sustainable break rate and the current break rate of an individual pipe to determine the optimal time of replacement is given. The sustainable economical break rate is obtained by minimizing the total cost resulting from replacement and repairs. It yields some of the previously available replacement criteria under weaker restrictions. Equivalence relations are established between the derived threshold break rate and the rate of occurrence of failure (ROCOF) and the hazard rate functions. These statistical functions are fitted to each pipe's break record. Optimal replacement time is obtained by equating the sustainable break rate to the assessed (predicted) break rate from the ROCOF, and the hazard rate functions. Design charts to determine the optimal threshold break rate as a function of pipe diameter and discount rate can be generated. A numerical examples illustrating the methodology is included.

**Key Words**: water distribution systems, break rate, rehabilitation, renewal, failure, optimization

## 1. INTRODUCTION

Aging water distribution systems are faced with the problem of replacing pipes that have reached their useful life. Water utilities are concerned about the number of main breaks and the resulting direct and indirect costs. Pipes are unable to carry intended flows at required pressure heads due to tuberculation. They are also losing strength due to corrosion. To make matters worse, ever- expanding cities continually place growing demands on these pipes. These problems directly contribute to frequent breaks and the resulting repair/replacement and rehabilitation costs. A decision regarding continual repair or replacement involves assessing the failure mechanism and the associated contributing factors. The analysis should be focused at an individual pipe level. Assessing the failure mechanism of a pipe requires the data related to each break event. The degree of deterioration of a pipe can be assessed most accurately by actual visual inspection and a structural integrity test in the field while the pipe is still in operation.

However, this kind of exercise is simply impossible, especially if we are interested in every pipe in a system. In this case historical records and information related to each break event becomes the best resort. If an estimator that pinpoints the replacement time after which it is no longer economical to repair can be developed, such an estimator will be of great use to practicing engineers.

## 2. LITERATURE REVIEW

The ensuing review focuses on deteriorating pipes. The replacement prioritization techniques may be grouped under the following four categories: (1) Deterioration Point Assignment (DPA) schemes (2) Break Even Analysis, (3) Regression and Failure Probability Methods, and (4) Mechanistic Methods. It is assumed that certain policy based replacements such as replacing less than 6 inch diameter pipes in view of fire fighting and regulation based replacements such as replacing lead pipes will be performed in a routine manner.

### 2.1 Deterioration Point Assignment Schemes

In the deterioration point assignment schemes (DPA), a set of factors involved in pipe failures is identified. This may include age of pipe, pipe material, pipe size, type of soil, location, water pressure, discoloration and odor problems and history of previous breaks. Ordinal descriptions of these factors are associated with numerical failure score. For any pipe a total failure score is obtained by adding the failure scores of the factors for that pipe. If the total failure score exceeds a threshold value the pipe is considered a candidate for replacement/repair (Weston, Inc., 1997). The discriminatory power of the scheme is clearly limited and becomes an issue if there are other pipes competing for limited funding. Also, it is a here and now assessment and lacks the predictive power which is crucial for future course of action. McKay et al. (1999) present a condition index based on assignment of scores as practiced by the US Army Corps of Engineers for civil works in general.

### 2.2 Break Even Analysis

The break-even analysis is a cost based method. Break-even approach requires depositing certain sum at an interest rate and its compounded value should equal to the future repair and replacement costs. Typically, this method is combined with a pipe break projection model to assess the optimal replacement time.

### 2.3 Regression and Failure Probability Methods

The regression and failure probability methods are related to the DPA scheme in that they build on the same deterioration factors but can bring in a predictive capability by assessing the probability of survival. Comprehensive reviews are given in O'Day *et al.* (1986) and Mays (2000).

Shamir and Howard (1979) applied regression analysis to obtain a relationship for the breakage rate of a pipe as a function of time. This relationship was used to find the optimal timing of pipe replacement to minimize the total cost of repair and replacement. Walski and Pelliccia (1982) subscribed to the idea of the threshold break rate. They adopted Shamir and Howard's (1979) model for predicting break rates. They derived an optimal replacement time estimator by setting the total repair costs over a period to be equal to the replacement cost.

Male *et al.* (1990) described a procedure in which an arbitrary threshold break rate is fixed.

The analysis involved consideration of five alternatives: (1) replace after one or more breaks, (2) replace after two or more breaks, (3) replace after three or more breaks, (4) replace after four or more breaks, and (5) do nothing approach. Alternative 2 turned out to be the most aggressive policy. Male et al. also indicated that the choice of alternative is sensitive to the discount rate used in the calculation. A higher rate leads to a less aggressive policy and vise versa. Male et al. drew their conclusions from simulation runs. The present work yields a closed form analytical model which also illustrates the role of the various factors identified in Male et al.'s paper.

Clark *et al.* (1982) suggested a model that combines two equations, one to predict the time to the first break and the second to predict the number of subsequent breaks which were assumed to grow exponentially over time in an attempt to account for the relative impacts of various external agents. Clark et al.(1982) have made the following observations: only a subset of pipes have recurrent repairs; the time to first repair is quite long, typically about fifteen years; the time between repairs becomes shorter as pipes get older; large diameter pipes tend to have fewer problems; and industrial development in general results in more repairs.

Kettler and Goulter (1985) provided regression equations for the number of breaks versus diameter and time for cast iron and for asbestos-concrete mains in Winnipeg, Canada. Their estimates showed strong inverse correlation between failures and diameter (0.0625 less annual failures/km of main with each cm of larger pipe diameter, for diameters between 10 and 30 cm). The correlation was 0.96. Comparisons with regressions on New York, Philadelphia and St. Catherines, Canada showed about 1/3 of decrease in failure rates per cm of diameter in these three cities in which failures were found to increase linearly with time.

Mavin (1996) provided a review of the failure models in the literature. Mavin also pointed out the need to filter the data before constructing a failure model. It was suggested not to include breaks that occurred within three years of installation and six months from a previous break repair. Based on the filtered data, a set of regression equations was constructed for number of failures over a time period and time interval between breaks. Marks et al.(1985) used multiple regression techniques to establish that the variables affecting the pipe breakage rate were pipe diameter, length of pipe section, age, pressure, type, soil corrosivity, intensity of land development, number of previous breaks, time to the second break, and period of installation.

Andreou *et al.* (1987) applied the proportional hazards model to predict failure probabilities of pipes in the early stages of deterioration and a Poisson model for the later stages of pipe deterioration. The basic idea of this model is to estimate a survivor function for each individual pipe, that will provide the probability for that pipe's survival beyond a future time period given a set of risk factors. The model provides the hazard function as a product of the baseline hazard function dependent only on time and a scaling factor made up of external variables such as pipe diameter, length, soil type, and land use.

Deb *et al.*, (1997) discussed a probabilistic model called KANEW to estimate miles of pipes to be replaced on an annual basis. The model uses the actual water main inventory, with the pipes categorized according to their age, material, diameter, and bedding quality. For each category $100^{th}$, $50^{th}$ and $25^{th}$ percentile ages are obtained either by expert opinion or by an analysis. These percentiles are utilized to obtain the three parameters of the Herz probability density function from which the survival probabilities are obtained. These survival probabilities are used to obtain the expected survivors or its complement of non-survivors per year, which are to be renewed. The procedure is applied to a bundle of pipes with similar makeup as opposed to an individual pipe.

### 2.4 Mechanistic Models

In addition, a number of researchers have developed mechanistic methods to model pipe failure phenomena. For modeling the change in pit depth with time, soil environment and age Rossum (1969) developed a set of equations based on the extensive data collected by the National Bureau of Standards (NBS) (Romanoff 1957). The NBS buried 36,500 specimens representing 333 varieties of materials in 47 soils starting in 1922. Only four soil types out of the 47 were considered not to have good fit. Kumar et al. (1984) provided a methodology for assessing corrosion growth in terms of a Corrosion Status Index (CSI) over time. The CSI depends on pipe coating, liquid carried, buried depth, soil resistivity, soil chlorides, soil sulfides, soil pH, soil moisture, pipe material, cathodic protection, and pipe diameter and wall thickness. Besides external corrosion, water mains are also prone to deteriorative mechanisms occurring internally. Through experiments Millette and Mavinic (1988) showed that the internal pipe deterioration through corrosion is dependent upon certain water quality and flow parameters. They reported the following findings: cast iron corroded twice as fast in a pressurized system as opposed to a gravity system and iron levels found in tap water exceeded levels found in raw water indicating the presence of corrosion and iron uptake by the water in the distribution system.

Wedge (1990) showed that the excess pressure developed in a piping system could amount to as much as 200 psi for a 10° F change in temperature. Pipe break data analysis of the Washington Suburban Sanitary Commission (WSSC, MD), water distribution system showed a trend in increased pipe breakage rate due to temperature drop (Habibian 1994). Temperature also affects the pipe in the form of increased loads that result from frost heaving of the soil. Monie and Clark (1974) found that the load on the buried pipe doubled due to frost heave. Also, frost conditions seemed to transmit live loads to the pipes from farther distances. Though the authors attributed increased number of breaks in pipes to frost loads, they also speculated that the cold water had the potential for increased stresses in the pipe thus leading to more failures. Cohen and Fielding (1979) and Rajani and Zahn (1996) provided analytical approaches for estimating the frost load. The mechanistic models account for overburden loads, surge pressure, expansive soil effect, thermal stresses and frost and strength loss due to wall thickness reduction These aspects are addressed in AWWA (2000) and Agbenowosi (2000). While these methods help to make the failure processes more understandable, the predictive capability has to be brought in either through a correlation analysis or through a probabilistic analysis by considering the parameters/variables to be random. Roberge (2000) contains a comprehensive review.

## 3. ECONOMICALLY SUSTAINABLE THRESHOLD BREAK RATE

In this section, an analytical methodology for optimal pipeline replacement is presented. The methodology provides the threshold break rate equation that gives the critical break rate for optimal replacement of a pipe. In addition, the methodology shows how the threshold break rate is related to general break rate, hazard, and intensity, also known as ROCOF (rate of occurrence of failure) functions. At the time of the nth break, a decision has to be made whether to replace the pipe at a cost of $F_n$ or to repair it at a cost of $C_n$. The scenario also implies that for the previous (n - 1) breaks only repairs have been performed. If we assume that the pipe will be replaced at the time of nth break, $t_n$, we can write the present worth of the total cost of the pipe as

$$T_n = \sum_{i=1}^{n} \frac{C_i}{(1+R)^{t_i}} + \frac{F_n}{(1+R)^{t_n}} \tag{1}$$

in which: R = annual interest rate (1/year), $t_i$ = time of ith break (year), $C_i$ = repair cost of ith break (\$), $F_n$ = replacement cost at time, $t_n$ (\$), $T_n$ = total cost at present time (time '0') in (\$).

When a pipe is new, it experiences very few breaks. An old pipe experiences more breaks under the same trench and load conditions. Therefore, the combination of time interval between breaks, relatively smaller repair cost, and a generally large replacement cost leads to the existence of a "U" shaped present worth of the total cost curve over time. The present analysis that leads to the derivation of the threshold break rate seeks to find the time of the minimum of the present worth of the total cost.

For the total cost $T_n$ at time $t_n$ to be a minimum, assuming a unimodal function, it must satisfy the condition,

$$T_{n-1} > T_n < T_{n+1} \tag{2}$$

For $T_n < T_{n-1}$, performing the needed calculation we obtain

$$t_n - t_{n-1} > \frac{\ln\left(\frac{C_n}{F_{n-1}} + \frac{F_n}{F_{n-1}}\right)}{\ln(1+R)} \tag{3}$$

Recognizing $t_n - t_{n-1}$ is the time between (n – 1)th and nth break or time interval for the occurrence of one break at time $t_n$ we obtain the threshold break rate, $Brk_{th,1}$, as the inverse of $\Delta t_n$ where $\Delta t_n = t_n - t_{n-1}$. That is the threshold break rate is defined as

$$Brk_{th,1} = \text{break rate between subsequent breaks} = \frac{1}{t_n - t_{n-1}} = \frac{1}{\Delta t_{n-1}} \tag{4}$$

Therefore, the threshold break rate is expressed as

$$Brk_{th,1} < \frac{\ln(1+R)}{\ln\left(\frac{C_n}{F_{n-1}} + \frac{F_n}{F_{n-1}}\right)} \tag{5}$$

By considering $T_{n+1} > T_n$ for a minimum we obtain

$$Brk_{th,2} > \frac{\ln(1+R)}{\ln\left(\frac{C_{n+1}}{F_n} + \frac{F_{n+1}}{F_n}\right)} \tag{6}$$

We define the optimal threshold break rate to be $Brk_{th}$ given by

$$Brk_{th} = \frac{\ln(1+R)}{\ln\left(\frac{C_{n+1}}{F_n} + \frac{F_{n+1}}{F_n}\right)} \tag{7}$$

Now from observed data for any given pipe we can derive a current break rate. Whenever the current break rate, $Brk_{cur}$ equals or exceeds $Brk_{th}$, the pipe should be replaced. In other words, if the condition for a pipe replacement at current time is expressed as

$$Brk_{cur} \geq Brk_{th} \tag{8}$$

Here, the importance of the term 'at current time' should be emphasized. If the current break rate is less than the threshold break rate and one wants to know when in the future the pipe needs to be replaced, he/she must be able to predict future break rate of the pipe and compare the predicted future break rate with the threshold break rate. However, the threshold break rate equation (7) does not involve predicting the future break rate of a pipe. Consequently, the use of the threshold break rate alone is limited to replacement decisions 'at current time'. This limitation of the use of the threshold break rate is overcome by a new methodology developed in this research in which the future optimal replacement time of a pipe can be obtained analytically by considering the relationships between the threshold break rate and statistical break prediction functions.

## 4. RELATIONSHIP BETWEEN THE THRESHOLD BREAK RATE AND GENERAL BREAK RATE, HAZARD, AND INTENSITY FUNCTIONS

A break rate function is generally defined as

$$r(t) = \lim_{\Delta t \to 0} \frac{\text{No.of breaks in}(t, t+\Delta t]}{\Delta t} \tag{9}$$

Eq. (9) can be expressed as a derivative of cumulative number of breaks function $N_c(t)$, that is

$$r(t) = \frac{dN_c(t)}{dt} \tag{10}$$

Since we are setting the time increment $\Delta t_n$ as the time elapsed from $t_n$, and $t_{n+1}$, the number of breaks in this interval is always 1. Therefore, an estimate of a break rate function at time $t_n$ is expressed as

$$r(t_n) = \frac{dN_c(t_n)}{dt} = \frac{1}{\Delta t_n} \tag{11}$$

Equation (11) has the same definition as the threshold break rate shown in Eq. (7). The hazard function, also known as the hazard rate and the instantaneous failure rate function, is defined by

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr[t < T \leq t+\Delta t \mid T > t]}{\Delta t} \tag{12}$$

where T is a failure time random variable. The hazard function expresses the propensity to fail in the next small interval of time, given survival to time t. That is, for small $\Delta t$,

$$h(t) \cdot \Delta t \approx \Pr[t < T \leq t+\Delta t \mid T > t] \tag{13}$$

The hazard function originally applies to non-repairable systems in which a failure implies the death of a system and is allowed only once in its lifetime. We assume here that a system gains new life after each repair. Therefore, similar to the case of a general break rate function, the estimate of the hazard function at time $t_n$ is expressed as

$$h_e(t_n) = \frac{N_c(t_{n+1}) - N_c(t_n)}{N_s(t_n)\Delta t_n} \quad (14)$$

where $N_c(t_n)$ is the cumulative number of breaks at time $t_n$ and $N_s(t_n)$ is the number of breaks expected to occur in time interval $\Delta t_n$. Now consider the situation in which we are continuously monitoring a pipe for every break. In such a case

$$N_c(t_{n+1}) - N_c(t_n) = 1 \quad (15)$$

and $N_s(t_n) = 1$. Therefore, the estimate of the hazard function at time $t_n$ is

$$h_e(t_n) = \frac{N_c(t_{n+1}) - N_c(t_n)}{N_s(t_n)\Delta t_n} = \frac{1}{\Delta t_n} \quad (16)$$

Equation (16) has the same definition as the threshold break rate shown in Eq. (7). The intensity function, also known as ROCOF (rate of occurrence of failure), is defined as

$$\lambda(t) = \frac{d}{dt}E[N(t)] \quad (17)$$

Similar to the case of the hazard and the general break rate function, the estimate of the intensity function at time $t_n$ is obtained by considering the failure rate between successive breaks. Since the number of breaks in time interval ($t_n$, $t_n + \Delta t_n$), in which $\Delta t_n = t_{n+1} - t_n$, is 1,

$$\lambda(t_n) = \frac{\text{No. of failures in } (t_n, t_n + \Delta t_n]}{\Delta t_n} = \frac{1}{\Delta t_n} \quad (18)$$

As we can see from Eqs. (11), (16), and (18), once we have the threshold break rate of a pipe by using Eq. (7) and have established an appropriate break rate, hazard, or intensity function, we can obtain the optimal replacement time of a pipe.

## 5. EXPONENTIAL BREAK RATE MODEL

As an example, consider the equation (Shamir and Howard, 1979)

$$N(t) = N(t_0)e^{A(t-t_0)} \quad (19)$$

in which: $N(t)$ = number of breaks per 1000 ft length of pipe in year t; t = time in years; $t_0$ = base year for the analysis(pipe installation year, or the first year for which data are available); A = growth rate coefficient (1/year). In our notation $N(t)$ is the break rate (that is, number of breaks/year at year t). Therefore, by setting $N(t) = Brk_{th}$ in Eq. (19) we obtain

$$N(t) = N(t_0)e^{A(t-t_0)} = \frac{\ln(1+R)}{\ln\left(\frac{C_{n+1}}{F_n} + \frac{F_{n+1}}{F_n}\right)} \quad (20)$$

Assuming $F_{n+1} \approx F_n$ at a rapidly deteriorating stage in which breaks occur in quick succession, and for small x, putting

$$\ln(1+x) = x \quad (21)$$

we obtain

$$t^* = t_0 + \frac{1}{A}\ln\left[\frac{\ln(1+R)F_n}{N(t_0)C_{n+1}}\right] \quad (22)$$

which is the same as the Shamir and Howard's result but obtained without losing the discrete nature of the events.

## 6. PRACTICAL USAGE OF THE THRESHOLD BREAK RATE

By using the threshold break rate equation a series of graphs and tables can be generated for practical uses. The threshold break is expressed as:

$$Brk_{th} = \frac{\ln(1+R)}{\ln\left(1+\frac{C}{F*L}\right)} \quad (23)$$

where: F is replacement cost per unit length of a pipe ($/ft) and L is the length of a pipe (ft). If a linear relationship is assumed between diameter and the cost ratio (C/F) as C/F = A*D + B, where: A and B are regression coefficients and D is diameter of pipe. Table 1 shows replacement cost per unit length (ft) and repair cost per break incident used in this study. Using this information, the equation for the cost ratio is obtained as C/F = 74.056 D – 7.204, where: D is the diameter (ft) of pipe.

**Table 1. Cost Table by Pipe Size**

| Size(inch) | Replacement Cost ($/ft) | Repair Cost($) |
|---|---|---|
| 6 | 92.77 | 2814.00 |
| 8 | 96.95 | 3985.00 |
| 10 | 106.50 | 5869.00 |
| 12 | 116.05 | 7753.00 |

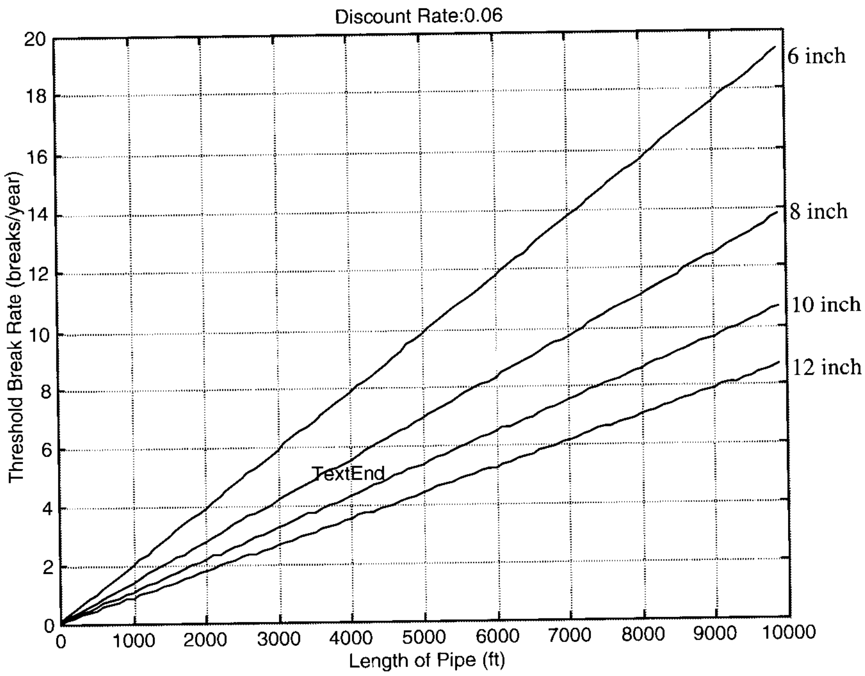


**Fig. 1. Threshold Break Rate Graphs for Pipe Size and Length (Discount Rate = 0.06)**

**Table 2. Pipe data**

| PIPE ID | Installation (year) | Length (ft) | Discount Rate (%) | Installation cost per ft. ($/ft) | Repair-cost per break ($) |
|---|---|---|---|---|---|
| 14449-1952-CI-6 | 1952 | 1363.5 | 7% | 92.77 | 2814 |

**Table 3. Break times from the database**

| MTB(1) | MTB(2) | MTB(3) | MTB(4) | MTB(5) | MTB(6) | MTB(7) | MTB(8) |
|---|---|---|---|---|---|---|---|
| 277 | 361 | 373 | 426 | 437 | 469 | 480 | 546 |

Therefore, Eq. (23) is expressed as

$$Brk_{th} = \frac{\ln(1+R)}{\ln\left(1+\frac{74.056 * D - 7.204}{L}\right)} \quad (24)$$

By using Eq. (24) a series of graphs can be obtained to determine the threshold break rates for different sizes of pipes for a given length and discount rate. Fig. 1 shows an example.

According to Fig. 1, 10 inch pipe should be replaced when the break rate (breaks/year) reaches 5 given a length of 4000 ft and a discount rate is 0.06. On the other hand the threshold break rate of 8 inch pipe is shown to be about 5.5 given the length and the discount rate the same as 10 inch pipe. However, this result does not imply that bigger size pipes should be replaced more frequently than smaller size pipes. Since it takes a longer time for a bigger pipe to reach a certain threshold break rate than a smaller one, one should not confuse threshold break rate with optimal replacement time.

## 7. NUMERICAL EXAMPLE

**Example:** Consider the following pipe break data (Tables 2 and 3) as a function of pipe age for a 6-inch cast iron pipe that was installed in 1932. The recorded historic break times in *months* of the pipe, 14449-1952-CI-6, obtained from the break database are shown in Table 3. In Table 3, MTB(i) stands for "months to the $i^{th}$ break from the installation". Calculate the optimal replacement time.

**Solution:** The cumulative number of breaks is plotted against number of years from installation (see Figure 2). The fitted equation for the cumulative number of breaks by the ith year given by

$$y_i = (1 - wf)(B_{lin} + A_{lin}x_i) + wf.B_{exp}e^{A_{exp}x_i} \quad (25)$$

and from Table 4 using the fitted parameters (25)

$$y_i = (1-wf)(-8.6486490.38378x_i) + wf \cdot 0.06578e^{0.11736x_i} \quad (26)$$

in which: $x_i$ = age in *years* for the number of cumulative breaks,i, $A_{lin}$, $B_{lin}$, $A_{exp}$, $B_{exp}$, and wf are parameters. From Fig. 2, it is seen that the equation fits the data past the age of 25 years. In

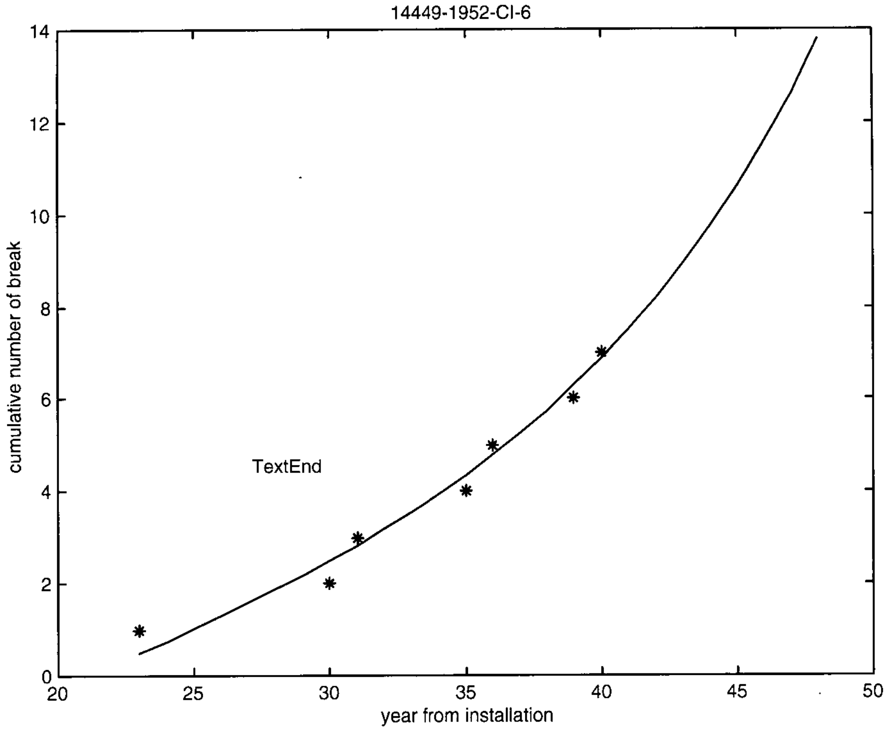


**Fig. 2. Cumulative number of breaks for "14449-1952-CI-6"**

**Table 4. Data required for replacement analysis**

| Pipe# | 14449-1952-CI-6 |
|---|---|
| $Brk_{th}$ (Threshold rate for present breaks) | 3.075023911 |
| $A_{lin}$ (Parameter) | 0.38378 |
| $B_{lin}$ (Parameter) | -8.648649 |
| $A_{exp}$ (Parameter) | 0.11736 |
| $B_{exp}$ (Parameter) | 0.06578 |
| Wf (Weighting factor) | 0.47 |
| GBRM | 56.86645941 |
| Replacement Cost | 126491.895 |
| Year of Installation | 1952 |
| Replacement Year | 2009 |

Table 4, the GBRM parameter refers to the optimal replacement time, $t_l$* obtained from the derivative of the fitted equation above (eq.(26)) and the threshold break rate (eq.23) and is given as

$$t_l^* = \frac{1}{A_{exp}} \ln\left( \frac{Brk_{th} - (1 - WF)A_{lin}}{wf * A_{exp} * B_{exp} * e^{-Aexe*t_0}} \right) =$$

$$\frac{1}{0.117} \ln\left( \frac{3.08 - (1 - 0.47)0.38378}{0.47 \times 0.117 \times 0.0676 \times e^{-0.117*0}} \right) \cong 57 \quad (27)$$

Based on the optimal age of replacement of 57, we have the replacement year as 1952 + 57 = 2009. Additional discussion and examples are given in Park (2000).

## 9. SUMMARY

In this paper a threshold break rate has been derived. In contrast to the previous studies the derivation does not embed a rate of break occurrence model. The threshold break rate entails the important conclusions drawn in terms of the discount rate and repair to replacement cost ratio by Male et al. (1990). It yields the same optimal time of replacement as obtained by Shamir and Howard (1979) but with less restrictive assumptions. Further more, the equivalence between the threshold break rate and the statistical failure modeling functions of rate of occurrence of failure and hazard functions is established. These functions provide a broad modeling environment for predicting pipe break rate from break database. By setting the threshold break rate to be equal to the projected pipe break rates from the ROCOF and the hazard rate analyses, optimal replacement time expressions are obtained. A numerical example illustrates the methodology developed in this paper.

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