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An Analysis of Watermain Replacement Strategies: Calgary Case Study

By

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ABSTRACT

Water distribution maintenance decisions present a very difficult multiobjective problem. Deterioration of those systems results primarily in breaks and leaks in pipes and also in a reduction in carrying capacity from tuberculation of the interior pipe wall. Large investments are generally required for replacement and repair of water mains and it thus becomes critical to assess the current and expected future conditions of the system that influence maintenance decisions.

The goal of this work is to study the frequency and causes of failures in water distribution systems. Data for this study is taken from the Calgary water mains. This system was chosen because it had readily available data. Statistical models are developed that demonstrate some of the factors leading to the deterioration of the water distribution system. The economic implications of various replacement strategies on the system cost are also examined.

A water distribution system represents a major investment for any municipality. Because of the potential health and safety implications, maintaining this system in good condition is extremely important for water utility management. Once a pipe begins to break, its break rate tends to increase exponentially resulting in increased maintenance costs. Therefore, scheduling maintenance and replacement is extremely important from an economic and reliability point of view. In this study, internal corrosion effects, cleaning and lining processes are not taken into consideration.

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NOTATIONS

A_1	Number of breaks per link year t_0.
A_2	Annual growth rate of pipe deterioration, ($year^{-1}$).
e	Base of natural logarithm (2.718).
C_r	Cost to replace a pipe, (\$ per link).
C_b	Cost to repair a break, (\$/break).
R	Discount rate of interest, (%).
t_0	Base time of the pipe deterioration, (years).
t	Time, years.
$N(t)$	Annual number of pipe breaks in year t, (breaks per 1000 ft.).
$C_m(t)$	Cost of repairing the breaks per link of a pipe in year t.
t_p	Present year.
$P_m(t_r)$	Future maintenance costs from (t_p to t_r).
$P_r(t_r)$	Future replacement costs from (t_p to t_r).
$P_t(t_r)$	Total costs of repair and replacement at time (t_r).
t_r^*	Optimal time for replacement, (years).
t_c^*	Length of the optimal replacement cycle, (years).
P_m^*	Total maintenance cost at time t_c^*, (\$).
$P_m(t_c^*)$	Total cost of repair for one cycle, (\$).
P_r^*	Total costs of repair and replacement for one cycle, (\$).
$\beta_1, \beta_2, ..., \beta_p$ and $\alpha_1, \alpha_2, ..., \alpha_p$	True values of the coefficients of independent variables.
$b_1, b_2, ..., b_p$	Estimates of the coefficients of independent variables.

n	Number of observations.
p	Number of independent variables in the model.
Y_i	Response or dependent variable.
$\bar{Y}_i$	Mean of response or dependent variable.
$X_1, X_2, ..., X_p$	Independent variables.
$\hat{Y}_1, \hat{Y}_2, ..., \hat{Y}_n$	Fitted values of the dependent variables.
β_0	Estimated y intercept when all X_i=0.
ϵ_i	Random errors associated with nth observation.
R^2	Multiple correlation coefficient.
S	Standard error of the regression equation.
S_Y	Variance of the dependent variable.
t	t-statistic of the regression coefficients.
Df	Degree of freedom at each variation of regression.
F	F-statistic of the regression model.
SS_{REG}	Sum of squares explained by the entire regression model.
SS_{RES}	Residuals or unexplained sum of squares.

Chapter 1

INTRODUCTION

1.1 Water Main Problems

There is a growing concern about the condition of the public infrastructure, including urban water supply systems. The condition of water mains and the reliability of services they provide are strongly connected with community public health standards and potential for future growth and economic development. Two different types of problems are causing great concern today in many utilities:

1. Breaks and leaks occurring at increasing rates along the pipe sections, and
2. Reduction in the carrying capacity of pipes due to tuberculation.

The above problems result in increased future repair and pumping costs, unreliable services, potential for damages caused by breaks (flooding, and disruption in traffic), and water quality problems caused from bacteria trapped in the tubercle formed in the interior wall of the pipe. Remedies for the above problems consist of replacing or rehabilitating sections of pipes in the system and represent large and important capital investments made by the water utilities.

In order to make repair or replacement decisions for deteriorating water mains, it is necessary to develop insights about the failure mechanism and the interactions of the various factors contributing to breaks, so that the predictions on the evolution of break trends with time could be made under various maintenance conditions. However, great difficulties arise when one attempts to analyze and predict the future behavior of individual pipes in a system, because of the high variability in failure patterns among different systems and among the various pipes of a given system. Nevertheless, such analysis at the individual pipe level is what is clearly needed for making maintenance decisions, using specific economic and reliability criteria. Although, on-site observations of the physical condition of the water mains can reveal some information about their structural integrity, such an approach would mainly be useful only when severe deterioration is present. Otherwise, the localized nature of various factors contributing to breaks, their interactions and the effect of the aging of the system cannot really be obtained by inspections of particular points along the pipe length. Therefore, it is necessary to analyze historical records of pipe breaks, and make use of all the available information on pipe characteristics and external environmental conditions, in order to develop a basic understanding of the existing failure patterns. Assessing with reasonable accuracy the expected number of future break events for each individual pipe can serve the following important goals:

1. Estimation of the expected repair costs under various replacement strategies.

2. Economic evaluations to determine an optimum replacement time for breaking mains.
3. Prediction of the reliability of individual pipes in the network.

1.2 Overview of Repair and Replacement Alternatives

Conditions in many aging mature water distribution systems have reached the point where upgrading is required urgently to improve reliability and maintainability. Factors that need to be addressed immediately include the increasing numbers of leaks and breaks, the high percentage of unaccountable water losses and the rising energy cost required for additional pumping caused by the loss of carrying capacity in aging mains.

There are three primary maintenance alternatives for dealing with leaking pipe systems. The first of these is directed at reducing water losses, and includes repair and replacement of deteriorated metering systems as well as leak detection. Although this is an important aspect of any maintenance program, the focus of this study will mainly be the two other maintenance programs, the repair and replacement alternatives.

1.2.1 The Replacement Alternative

The replacement alternative is usually considered the appropriate strategy for long-term reduction in the number of leaks and breaks in water mains. It is also the strategy used in areas of high growth where the pipes are of inadequate size for the expansion requirements of the system. Replacement is generally recommended for pipes which have experienced extensive breaks or leaks in the past and is not recommended for those that have remained structurally sound.

1.2.2 The Repair Alternative

Repair, in this context, is usually recommended for pipes which did not reach the critical age in terms of failure during their lifetime. The critical age of a section of pipe occurs when the probability of failure is such that replacement is the economical alternative to increased maintenance and repair costs. In large mains, where low break frequencies keep expected repair costs low, management may consider rehabilitation (i.e., repair), since replacement of large mains is very expensive (often about double the cost of rehabilitation).

1.3 Objectives

The objective of this work is :

1. To analyze break records and develop an applicable formula for predicting breaks based on statistical techniques.
2. To attempt to apply these predicting models for making pipe repair and replacement decisions.

The proposed methodology will be used in studying the data of pipe break records for the city of Calgary, Canada.

Chapter 2

LITERATURE REVIEW

2.1 General

Current knowledge about the failure mechanism in water mains lacks a clear understanding of the interactions of the various factors contributing to breaks. It is indeed extremely difficult to model the combined effects of corrosion (internal and external), improper bedding conditions, stresses from external loads, stresses from high internal pressure and properties of particular pipe materials that have changed through the years. Thus, although several factors associated with breaks can be identified, there is no coherent model describing the changes in the physical condition and structural integrity of a main with time, under the presence of those factors. This situation has led to the development of several empirical methods for assessing the future performance of deteriorating pipes and for making replacement and rehabilitation decisions. Statistical techniques based on historical break records have also been applied in order to develop greater insights about the failure patterns and to quantify with greater accuracy existing trends. Many of the current empirical methods recommend, for example, replacements based solely on pipe age and number of previous breaks. Clearly more scientific work is needed in order to examine whether reliance on such measures is justifiable.

2.2 Descriptive Statistical Studies for Pipe Deterioration

Descriptive statistical studies have been performed on several occasions for analyzing pipe failures. Although studies have revealed useful trends in the behaviour of deteriorating pipes, many questions concerning the effect of aging on the break rate and the ability to provide reliable quantitative measures for assessing the condition of the water main, have remained unanswered.

Generally speaking, studies have usually concentrated on the analysis of pipe failures in identifying trends in the overall system. However most studies do not deal with the high variability in failure patterns that exist among different pipes of a given system. The summary of the most representative studies of this type are presented in the following section.

A recent statistical analysis of main failures in the City of Philadelphia [34] showed the following:

- Break rates have increased at 1.8% per year since 1930.
- The rate of water main breaks increases significantly in the past twenty years, at an annual rate of 2.5%
- In terms of pipe diameter, break rates in small diameter mains are

more frequent than with larger diameter mains ($\geq$ 16" or 400mm). Also, in terms of break-type, circumferential breaks represented 71% of the breaks in the 6"(150mm) diameter pipes, dropping to 34% and 31% for 12"(300mm) and 16"(400mm) mains respectively. Longitudinal breaks varied from 18% in 6"(150mm) pipes to 47% for 10"(250mm) pipes.

For pipes buried during the 1940-1960 period, a high break rate has been observed. An important factor, is the use, during that period, of a leadite joint material, which causes a joint to become rigid, instead of a lead material that was used in the past and which allowed the joint to be more flexible. Therefore, a leadite joint material could restrain the pipe from thermal contraction or extraction and cause stresses that result in technical failure of the pipe.

- The investigation of the relationship between pipe age and break rate did not lead to any satisfactory conclusion in terms of the effect of age alone on pipe failures. Although, older mains, on average, were found to experience higher break rates, it is argued that age should not be used alone as a criterion for replacement decisions.

- Water quality effects, specifically internal corrosion, was found to affect significantly the main and reduce the wall thickness of most of the pipes examined in a sample test; and also it was found to penetrate deeper than external corrosion. It has, thus, been established that internal corrosion not only leads to the formation of tubercles which will block off the flow in the main, but it also contributes significantly to the undermining of the structural integrity of pipe.

A statistical analysis has been performed for the city of Buffalo, New York, by the US Army Corps of Engineers [45]. Its major findings revealed a very seasonal pattern in main breaks with the majority of breaks also being in the smaller diameter pipes. The only difference in the seasonality patterns found between that study and the one performed for the city of Philadelphia [34], is that in Buffalo, the break rate increased not only during the winter months but also during the summer months of high demands. The reason could be because of the increase in operating pressures in the system to meet demands during that period.

Generally speaking, most of the statistical studies performed on various cities [27] have observed a high break rate during winter months. External forces on pipes induced by frost penetration and restraints caused by thermal contraction, are considered to be the primary causes of this trend. Clearly, those forces will depend on factors such as soil type, pipe material and environmental conditions.

A general controversy exists in the literature about the effect of the aging on pipe failures. As previously mentioned, the Manhattan and Philadelphia studies [27, 34], basically, demonstrate that the age of the pipe must be only a minor consideration in the main replacement program. The Manhattan study team found that the mains were not wearing out with age. The Philadelphia team found a very weak correlation between break rate and age of mains when they looked at 6"(150mm) diameter mains and they also found a higher number of breaks on average for older mains. Clark et al. [4], on the other hand, in their attempt to derive a predictive model for pipe break failures found that the age of metallic (cast iron and steel) pipe was an important factor in predicting future breaks for a main segment.

A probable reason for this controversy lies in the fact that the relationship between age of the pipe and break failures is a very complex one and cannot be captured by simplified statistical analysis techniques. Although, intuitively, it seems that the age-related factors, such as pipe material, design and construction practices at the time the pipe was laid, and deterioration due to corrosion, could result in a relationship between age and break rate, its form has not been established in the literature. The effect of aging is expected to eventually contribute to the failure rate later in the life of the pipe.

The descriptive statistical studies for deteriorating water distribution systems have provided us with great insights about the failure patterns and possible break-causing factors of water mains but such analyses also have major weaknesses.

- They do not provide useful information about the failure pattern of individual segments.
- The complex interaction among the various break causing factors cannot be assessed in detail.

2.3 Predictive Models for Pipe Failures

The need to obtain a quantitative decision tool for making repair versus replacement decisions for deteriorating water pipes has led to the derivation of predictive models for pipe break failures. There are three basic categories of models developed at present:

1. Aggregate-type models, where the expected number of breaks is a function of time, a reference time period and certain constant model parameters.
2. Regression-type models, where the expected number of breaks, or the expected time to the next break, are predicted as a function of

certain independent variables reflecting environmental conditions and pipe characteristics, and

3. Probabilistic or choice models, where discriminant analysis is applied to the data.

2.3.1 Aggregate-Type Models

This type of model was proposed first by Shamir and Howard [40]. Two equations were used (one linear and one exponential) to describe the break rate as a function of time:

$$N(t) = N(t_0)e^{A(t-t_0)} \tag{2.1}$$

and

$$N(t) = N(t_0) + A(t - t_0) \tag{2.2}$$

where,
N= number of breaks in year t, (breaks/ length/ time);
t_0= base year, (time);
A= rate constant, (breaks/ length/ time); and
t= year, (time).

The exponential model is the one most used in the describing of the deterioration of watermains. However, the application of either the linear or the exponential models depend mainly on the characteristics of the pipe material and its environment.

Later, Walski and Pelliccia [49] proposed another model for determining the optimal replacement time, based on a study of historical records from Binghamton, New York. An exponential function similar to that described by Shamir and Howard was fitted to the data with diameter, pipe type, age, and the number of previous breaks as covariates. A function was derived predicting the break rate for each pipe for any year in the future.

$$N(t) = c_1 c_2 N(t_0) e^{A(t-t_0)} \tag{2.3}$$

Where,
c_1= correction factor for previous breaks of the pipe, and
c_2= correction factor for pipe size.

The focus of the above approach was the economics of the maintenance alternatives. Costs of water main repair and replacement were evaluated in detail and provided the basis for the decisions of whether to replace or repair a main. Such decisions were to be determined from the present worth of the costs of repair and replacement, applying an optimal time analysis like that in the Shamir and Howard model. The main difference in method between Walski and Pelliccia's model and that described by Shamir and Howard is the detailed analysis of the costs involved in water repair and replacement. It is important to note that the pipes are considered with similar characteristics and pooled together. The primary limitation of this model is the apparently arbitrary selection of correction factors for predicting the number of breaks, such as the previous break factor and the pipe size factor.

In the literature, the values of the rate constant, A, proposed by Shamir and Howard [40] are in the range of 0.01 to 0.15. When Clark [5] applied a similar modelling approach, he found a value of 0.086, while Walski [49] found values of 0.021 and 0.014 for pit cast iron and sandspun cast iron pipes respectively. The above modelling approach was the first forecasting technique that used the number of breaks to predict the optimal year in which a pipe should be replaced. Its major advantage is its simplicity, however, it has weaknesses which can be summarized as follows:

- It does not give any insight about the failure-causing mechanism and the factors contributing to main failures, that is, it does not distinguish between pipe characteristics, environmental factors and previous break history of the pipe.
- These studies do not give any information about the statistical significance of the coefficients and the goodness of fit tests of the models.

In summary, the application of such models for making repair versus replacement decisions of water mains could lead to suboptimal replacement strategies, since their focus is not at the individual pipe level. Again, since the statistical validity of these models was not established, the reliability of their predictions cannot be determined. Nevertheless, they have an advantage of being simple and do not require large amount of data as compared to other regression models.

2.3.2 Multiple Regression-Type Models

A multiple regression type model determines if a linear relationship exists between dependent variables and independent variable. Clark et al [4], based on the Cincinnati study (1982), developed two equations. The first estimates the time to the first maintenance event and the second estimates the number of maintenance events after the first event.

The first equation, which estimates the time to the first event, had the following form

$$Ny = 4.13 + 0.338D - 0.022P - 0.265I - 0.0983Res - 0.0003Lh + 13.28T \tag{2.4}$$

Coefficient of determination, R^2=0.23
in which

Ny= number of years from installation to first repair;
D= diameter of the pipe, in inches;
P= absolute pressure within the pipe, in pounds per square inch;
I= percent of pipe overlain by industrial development in a census tract, in %;
Re= percent of pipe overlain by residential development in census tract, in %;
Lh= length of pipe in highly corrosive soil, in feet; and
T= type of pipe, (1= metallic, and 0= reinforced concrete).

The second equation estimates the number of events occurring after the first event,

$$Rep = (0.1721)(e^{0.7197})^{T}(e^{0.0044})^{Prd}(e^{0.0865})^{A}(e^{0.0121})^{Dev}(Sl)^{0.014}(Sh)^{0.069} \tag{2.5}$$

Coefficient of determination, R^2=0.47
in which,
Rep= number of repairs;
T= type of pipe, (1= metallic, and 0= reinforced concrete);
Prd= pressure differential, in pounds per square inch;
A= age of pipe from the first break;
Dev= Percent of land over pipe in low and moderately corrosive soil;
Sl= surface area of pipe in low corrosive soil, in feet square; and
Sh= surface area of pipe in highly corrosive soil, in feet square.

From the above models, it appears that the goodness of fit test (indicated by the coefficient of determination, R^2, which indicates the percentage of the total variation explained by the regression equation) shows a rather unsatisfactory fit of models, particularly for model (2.4). In addition, we do not know how statistically significant the estimated coefficients are. It can be seen that the evaluation of the statistical significance of each variable appearing in the equation is not possible, so the calculated R^2 could be artificially high.

It is clear that this type of model can generate significantly greater insights about the key factors related to failures in water mains and can also be much helpful for replacement decisions than the model proposed by Shamir and Howard [40]. However, problems associated with the availability of appropriate data can limit their application in real world problems.

2.3.3 Probabilistic-Type Models

In this type of model, the focus is upon the estimation of the probability that a break will occur at some future time. In the literature, the discriminant analysis is the only one which has been applied in the past to water main failure data [34]. The purpose of the discriminant analysis can be to find:

1. A mathematical rule, or discriminant function, for determining which class an observation belongs to, based on knowledge of the quantitative variables only.
2. A set of linear combinations of the quantitative variables that reveals the differences among the classes, or
3. A set of the quantitative variables that best reveals the differences among the classes.

Finally, some observations can be drawn regarding the application of such models:

- The effect of the aging on water pipes was not included in the derived models, which makes their predictive power limited to long-term periods.

- In the analysis, the water pipes were classified in only two groups, those that have broken and those that have not. It, therefore, fails to follow the evolution of failure patterns and failure mechanism of individual water pipes.

Chapter 3

ANALYSIS OF THE CALGARY MAINS

3.1 General Characteristics of the System

There were 2750 km of buried water pipes in Calgary at the end of 198C, [3]. The system consisted of pipes made of cast iron 45%, ductile iron 42%, concrete 5.4% and others 7.6%. Review of more than 13,500 failure reports revealed that failures in the water distribution system occur most frequently in pipes. Ninety-two percent of the failures that appeared over a period of twenty-five years (1956 -1980) were associated with failures of pipes; service saddles accounted for 6.2% of the failures while the remaining cases of failures, 1.8%, concerned fittings such as valves, hydrants and service rods. Until 1963, about 90% of the pressure water pipes in Calgary were made of cast iron with the balance made of steel, asbestos-cement and cement. Since 1963, the cast iron pipes have been gradually replaced by pipes of different materials, mostly ductile iron. As of 1980, there were still

1236 km of cast iron water mains in Calgary, i.e., 45% of the total installed length. However, the length of cast iron piping in the ground has been gradually decreasing because sections of the mains which have deteriorated are being replaced with pipes made of other materials. Ductile iron pipes were introduced into the Calgary water distribution system in 1963 in order to replace cast iron piping. By the end of 1980, there were 1144 km of ductile iron pipes in the ground, i.e., 41.6% of all pipes in service. Table (3.1) summarizes the characteristics of the Calgary water mains.

3.2 General Problems Associated with the Data

One of the most important problems to be considered when dealing with the derivation of a predictive model for pipe break failures is the availability of adequate and reliable data. There is a great variability among the records kept in various utilities concerning repair events for water mains, environmental characteristics, operating and maintenance practices and pipe materials. An underlying factor in most cases is that records were not collected and organized for the reasons they are expected to be used today. Although problems with data sets will always exist, information obtained by analyzing a data set, despite all the problems, can be useful in generating insights and helpful in making repair and replacement decisions. However, some data is unreliable for use in a more sophisticated analysis. Finally, it must be kept in mind that analyzing an imperfect data set could also generate insights about the proper collection of future data, as it will be pointed out in this study.

Table 3.1: Characteristics of the Calgary Watermain Model.

Item	Description
Pipe type	87% iron (Cast and Ductile), 5.4% Concrete, 7.6% other materials
Diameter	ranging from 4-16 inches
Soil Stability	59% of pipes in stable soil 35% of pipes in moderately stable soil
Soil type	About 54% is Clay, 20% is Silty-clay, and 26% Others (Gravel, Sand, Silt, etc.)
Date of Installation	50% installed during 1956 and 1963 small cluster in other years
Time to first break	Ranging from 5 to 26 years
Percent of breaks	81% in Cast iron pipes, 9.8% Ductile iron pipes, 0.8 concrete and 8.4% undefined.

3.2.1 Specific Problems

Breaks Versus Leaks

It is important to define the difference between a break and what we consider to be a leak. Clearly, this threshold should be related to the amount of discharge from the damaged main. Leaks from pipes are, as expected, much more difficult to detect than breaks which usually have an immediate impact at the system. Since the recorded break events very often represent repair events, a distinction should be made as to whether the repair was for a break or for a leak. Unfortunately this kind of information was missing in most of the cases.

During the course of this analysis, a break is defined as a rupture of the line causing a cessation of service. A more subtle and insidious occurrence was continuous leakage from certain pipes causing maintenance crews to take remedial action. Therefore, the analysis contained here is based on repairs, but not on actual ruptures. These breaks do not include leaks from valves or clamps, but only main line leaks.

Break-Type and Location

Information on break type is important, since different break types will, in general, relate to different break-causing factors. There are four basic break types in water mains:

- Circumferential breaks (ring cracks),
- Longitudinal breaks (split pipes),

- Holes in pipes, and
- Joint breaks.

In the case of the Calgary system, break-type had been recorded only for samples of pipes, taken at different points of the system. An analysis, however, has been performed in chapter (5), concerning the relation between break-type, seasonality, pipe characteristics and other environmental conditions.

The exact break location along a specified pipe length can be useful, when available, since it makes it possible to investigate whether subsequent breaks occur in the same location or not and also it might provide information on particularly unfavorable local conditions. Very often though, information on break location is missing from the data sets, which makes the distinction between localized and more extended pipe deterioration extremely difficult.

Pipe Diameter

Information on the pipe diameters is very useful in analyzing the system in terms of individual pipes. For the purposes of deriving statistical models, a pipe should correspond to an entity with uniform geometric and operating characteristics (diameter, pressure) along its length and on which uniform environmental conditions apply (soil type, external loads, etc.). In general, for only a limited samples of data, such information has been available.

Internal Pressure

The role of the internal pressure in the failure of the water pipes is debated in the literature. Clark et al [4] found that the internal pressure is an important factor only in pipes which had not broken. Andreou [5] showed, through the analysis of the Cincinnati system, that higher pressure increases the probability of future failures for pipes already broken once. Although it appears that high pressure does not cause a loss of pipe wall thickness by itself, with time, it is reasonable to argue that the stresses imposed on the pipe wall due to high pressure contribute to occurrence of a break if the wall is already eroded due to corrosion. Nevertheless, internal water pressure is usually missing from the data.

Previous Maintenance History

Previous maintenance practice (including anti-corrosion measures) are important, as long as they could affect the structural behaviour of the system. The utility's policy associated with leak detection can also be relevant, since a close relationship between leaks and breaks is expected to exist. Often, pipes that have been replaced due to bad performance still exist in the data sets and this could distort the results of a statistical analysis. Information on maintenance practices is not recorded on data sets, although it may, significantly help in explaining many of the observed failure patterns.

3.2.2 Additional Problems

It is very often the case that information on depth of cover for pipes is missing and also information on the exact timing of breaks (i.e., day and month as opposed to only years). That information could have been useful for judging the effect of frost penetration on pipe breaks and the exact stresses caused by external loads.

Information on flow velocities would also have been useful, since flow velocity is directly related to dynamic pressures developed in a conduit from water hammer and conduit bends. But again, this information is rarely available.

3.3 Descriptive Analysis

The major aspect in planning repair and replacement of water mains lies in an evaluation of the historical rate of deterioration of the pipes. A comprehensive evaluation of the condition of a water distribution system must consider these four elements:

1. Structural integrity of the pipes,
2. Water quality and contents,
3. Hydraulic conditions, and
4. Existing leaks.

The structural integrity of a main depends on the inherent strength of material used to manufacture it, its dimensions, and the effective thickness (taking corrosion into account) of its wall. Main breaks occur when a main's structural integrity is no longer sufficient to withstand the internal and external forces imposed on it.

Water quality parameters (hardness, pH, alkalinity, etc.) provide some indication on the effectiveness of water treatment plant processes in stabilizing the internal condition of unlined distribution mains in service. Internal pipe wall corrosion can adversely affect the quality of water by introducing corrosion products into the system, as well as the bacterial contamination. Except for the case of graphitization, all the inside surface of pipes were coated by cement-mortar lining. Beside that, there was a tendency for accumulation of thin and uniform deposits of different chemical substances such as $CaCO_3$ on all the inside pipe surfaces. It was assumed that the mineral scale protects the pipe interior against corrosion and water quality against corrosion products and bacterial contamination.

An evaluation of hydraulic conditions may help reveal the extent of water main deterioration. A reduction in the carrying capacity of a main can result from tubercles built upon the interior wall. Increased pumping levels may therefore be required to maintain minimum service pressure conditions, resulting in increase leakage rates and pumping costs. Because of the lack of information on the hydraulic conditions, this will not be the focus of the present analysis.

Water or service leakage incidents can accelerate a water main's failure rate. Water main leakage may washout the support soil bedding in the trench, thereby putting the main in a beam condition. Leakage may also promote accelerated external corrosion rates by increasing the moisture content of certain soil types with certain drainage characteristics.

It is extremely difficult to determine the underlying causes of water main failure due to the complex interrelationship of the many factors involved in the deterioration process. The condition of a water distribution system can vary dramatically by pipe class or geographic region. The strength of a main depends on both the inherent properties used to manufacture the pipe and the thickness of the pipe wall. A main's resistance to corrosion from the surrounding soil, and internal corrosion, as well as its ability to withstand physical forces (i.e., thermal contraction, internal pressure, external loads, and beam loading) also help determine its condition, Figure (3.1).

3.3.1 Structural Causes of Water Main Breaks

Water mains are structures that are stressed by both internal and external forces. As long as a main's strength exceeds the stresses caused by these factors, the main will give reliable, break-free service. When the stresses exceed the main's strength, the main will fail as a structure, which will result in a break. While this point may seem obvious, it is central to the required analysis and planning for water distribution system rehabilitation. The forces that act on a main include the following:

- Internal pressure including both working and surge pressure,
- External loads from earth, truck superload, and frost penetration,
- Beam loading if the main is not uniformly supported, and
- Thermal contraction if the main is restricted from expansion and contraction. Figure (3.1) presents the set of factors that affect both the forces on the main and those affecting the loss of pipe wall from internal, and external corrosion. Each factor indicated in Figure (3.1), can vary from main to main due to site-specific conditions such as soil characteristics, external loads, temperature effects, soil moisture, and pipe unit strength. The interplay of these factors in a given situation determines the structural condition of the main. Thus, a main of a given unit strength and effective pipe wall thickness may break

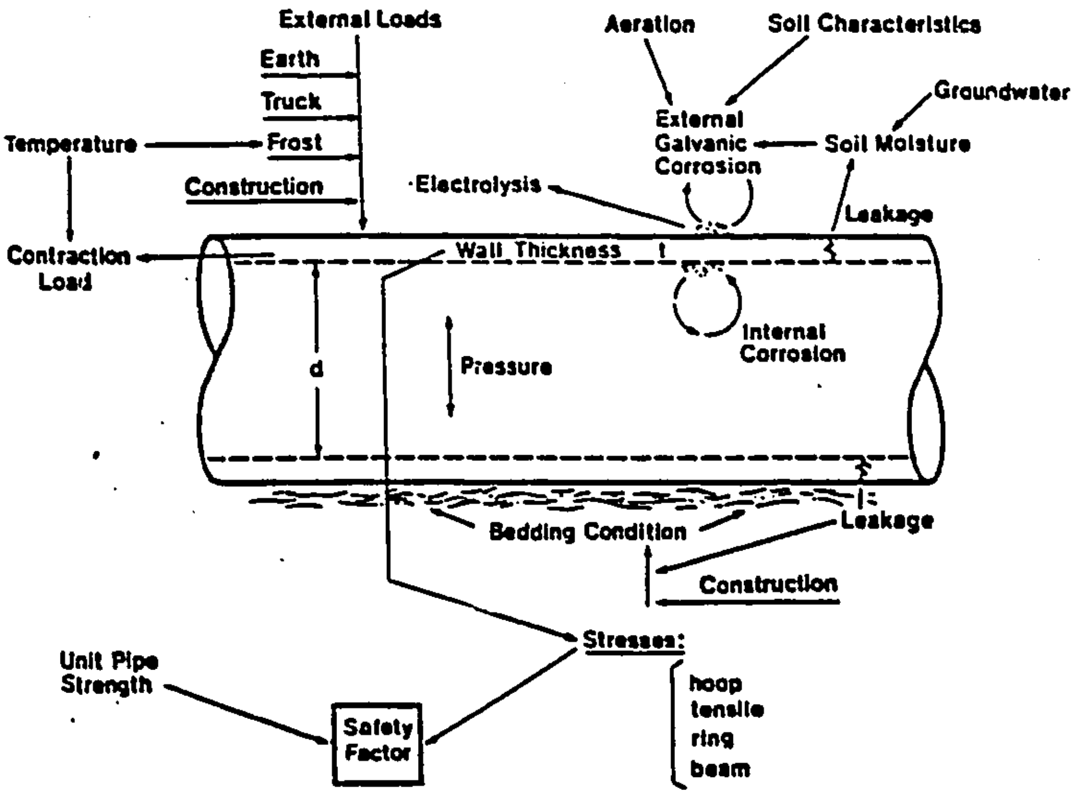

Figure 3.1: Conceptional Model of Watermain Structural Condition [4].

because the forces exceed its unit strength, while a weaker main at another location may function adequately because the forces on the main are less. It is necessary, therefore, to recognize the variety of conditions that exist across a water distribution system. It is the combination of a main's environmental conditions, the time the main is exposed to those conditions, and the forces exerted on the main that determines its structural condition.

3.3.2 Environmental Conditions

Role of Corrosion in Deterioration

The literature reflects a wide diversity of opinion on the relationship between corrosion and water main breaks. Fitzgerald [16] states:

"... It has been recognized, however, by water utility personnel that the majority of 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 ".

Fitzgerald's statement can be contrasted to statements in the US. General accounting office's Report to congress [16]:

"... External corrosion of cast iron mains does not appear to be the 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% of 121,500 miles of pipe in 229 cities was affected by corrosion. Pipe age ranged from new to 149 years old ".

These statements reflect considerable differences of opinion. Which is correct? In order to reconcile them, it will be necessary to review the corrosion process to provide background information on it.

Corrosion Process

Corrosion can be defined as the destruction of metal, usually caused by chemical or electrochemical reaction with the surrounding environment. Most metals are derived from natural metal ores, and when exposed to the elements of the environment they have an inherent tendency to revert to the stable forms in which they were originally found in the earth. A common example of this tendency is the rapid formation of iron rust when unprotected common steel surface is in contact with the environment. The rate of corrosion is largely dependant on the inhibition, or the resistance to the continuing progress of the reaction between the metal and its environment. This inhibition is dependent on the metal itself, and a variety of conditions involving the ionic components of the environment including dissolved oxygen, pH, temperature, and the degree of water saturation around the metal.

While there are many different types of corrosion, the most common type resulting in water main failures is "Galvanic Corrosion". Galvanic corrosion is associated with a contact of two different metals or alloys in the same environment, or the exposure of one piece of metal to multiple environments. As the different metals come together, or when a piece of pipe is exposed to the different environments, a current flow is generated creating an anodic area and a cathodic area. Electrons flow from the anode to the cathode. The elemental metal releases electrons at the anode area establishing an oxidized state of the metal. The oxidized metal may then be solublized in the electrolyte and removed from the cell.

Soil-Related Corrosion

The basic corrosion cell can exist in the soil when one piece of pipe is exposed to two different soil environments. The electrons are released at the cathode area, while the elemental metal is oxidized at the anode providing electrons to the metallic pipe and exposing oxidized metal to the environment. Since the cathode area does not lose metal, the cathode area is protected from corrosion, while the anode area is the corroded portion of the corrosion cell.

While galvanic corrosion is the type of corrosion in water distribution systems, it is important to remember that other types of corrosion may also exist, such as stray current corrosion. If not recognized, other types of corrosion may be incorrectly identified and improper corrective action may be taken.

Various environmental factors affect the rate at which metal is lost from a metallic pipe. These factors can be grouped in the following classifications:

1. water movement,
2. oxygen content,
3. soil type, and
4. soil resistivity.

Water movement is important for two reasons. First, rapid water movement through the immediate environment of the metallic pipe will have a tendency to remove corrosion products from the surface of the pipe. This removal will minimize the inhibiting action of the corrosion products and increase the corrosion rate on the pipe. Assuming all other environmental factors are the same, it has been proven that areas with sandy or loose soil characteristics will have a higher corrosion rate than areas of tight clay type soil [27]. This is due to the ability of loose soils to pass higher rates of water. Secondly, water is necessary for the existence of an electrolyte in the environment surrounding the pipe. In a totally dry environment, a current flow cannot exist, therefore corrosion cannot exist.

Dissolved oxygen is another factor that can affect the corrosion rate. It is not so much the oxygen content, but rather varying oxygen concentration which produces differential oxygen cells. These areas of differential oxygen cells will cause galvanic corrosion. This reaction may easily occur in soils that are low in dissolved oxygen prior to excavation and backfilled operations. These soils become aerated during excavation, and when backfilled create a higher oxygen content at the top of the pipe than at the bottom of the pipe, which is resting in the original soils. The low oxygen area becomes the anode, and the high oxygen area becomes the cathode. Thus a corrosion cell is created. The lack of the oxygen in the soil may also provide the necessary environment for what is commonly know as anaerobic bacterial corrosion. Basically, anaerobic corrosion is the result of sulfate-reducing bacteria consuming the hydrogen being produced at the cathode. By consuming the hydrogen, the inhibiting layer on the pipeline is eliminated allowing the corrosion current to increase.

The soil type determines the ability of water to move through the soil, and the amount of dissolved materials to provide the electrolyte in the environment around the pipe. Very tight soils, such as clays, allow a lower water migration and result in lower corrosion rates. However, they also have a tendency to be high in soluble ions which increases the corrosion rate. Conversely, sands exhibit very low solubility, but result in very rapid movement of water. Therefore, it is impossible to determine from the soil type alone whether a corrosion problem will exist.

However, by far one of the most important parameters is the resistivity of the soil environment around the metallic pipe. The lower the resistivity, the better is the current carrying environment that exists in the corrosion cell.

In summary, there are a number of parameters that can affect the rate at which an iron pipe corrodes in a naturally occurring soil environment. On a broad spectrum basis, one particular parameter cannot be utilized in the prediction of corrosion rates. A multi-parameter approach is most desirable in areas of varying soil environments.

Analysis of the Calgary Soil

Analysis of the statistical data provided by the city of Calgary [3], as well as chemical analysis of the soil samples collected at the failed pipe depth, indicate that except for some areas of sand along the river, the soil in Calgary is mostly clay and silty-clay. Resistivity of the soil sampled at sites where the lengths of failed pipes were collected varied from 560 to 4300 ohm-cm, with thirteen out of seventeen samples having resistivity lower than 1000 ohm-cm. These values are compatible with the statistical data of soil resistivity in most parts of Calgary except for soil along the river, where the resistivity is much higher. Roughly 75% of more than 13,500 pipe failures occurred in the Calgary distribution system, between 1956 and 1980 took place in clay and silty-clay soil while less than 11% of the failures were experienced in soil containing gravel, sand and silt as the prevailing constituents, Figure (3.2). The most frequently used criterion of soil corrosivity is soil resistivity, which is convenient and easy to determine in the field. Soils with high electrical conductance (low resistivity) are, as a

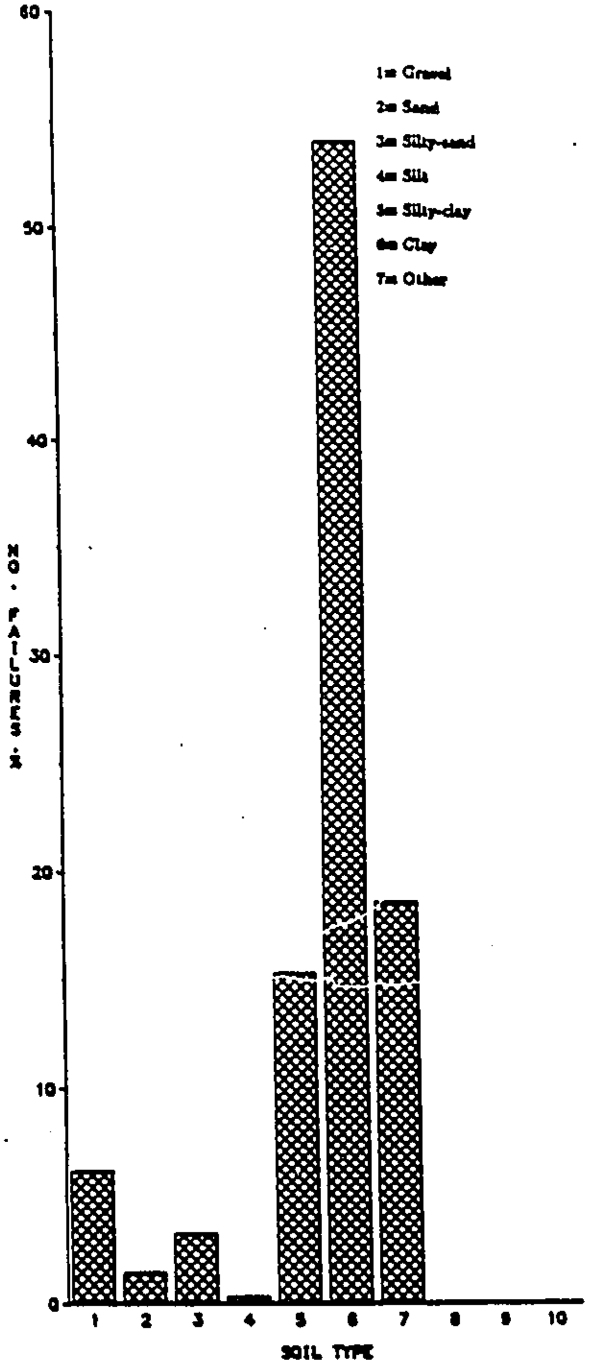

Figure 3.2: Distribution of Pipe Failures vs Soil Type.

rule, corrosive. On the other hand, the functioning of corrosion cells formed on metal surfaces is not determined completely by the electrical properties of the soil. Such important properties of the soil as degree of aeration, amount of moisture, sand content, pH, mineral contents and presence of some bacteria also affect the corrosion cells. A system developed by the Ductile Iron Pipe Research Association, commonly called the ten point system, reported in reference [2], is an attempt to use a multi-parameter approach of the corrosive potential of soils. This approach is presented in Tables (B.1, B.2). The table indicates the point ratings assigned to the different soil chemical parameters, with the total number of points indicating the quality of the soil. If the results of the soil test evaluation are zero or more, the soil is considered non-corrosive to metallic pipe, therefore protection of the pipe is not necessary. A point total ranging from −1 to −4, −5 to −10 or less indicates that the soil is moderately corrosive, corrosive or very corrosive to metallic pipe respectively, and the pipe needs to be protected. After examination of the Calgary soil Table (3.2), all analyzed samples fall into the category " corrosive ", except for one sample which was rated " very corrosive ".

Water-Related Corrosion

The destruction of the metallic pipe can also occur on its interior side, because of the chemical characteristics of the water. The water-related corrosion of unlined metallic pipes causes several problems, including loss of hydraulic capacity, water discoloration and loss of main wall. Its impact on hydraulic capacity and discoloration are well known. Unlined metal mains are particularly susceptible to internal corrosion, since the wall and the water contact directly. Internal corrosion will start at locations where the interior main wall surface is nonhomogeneous due to crevices, scratches, or rust. These different areas of the main wall create an electrical potential

Table 3.2: Indexation of Samples and Classification of Soil Corrosivity of Calgary

Soil Sample No.	Type of Soil	Soil Conditions Water Table	Soil Conditions Back-fill	Homo-geneity	Resist-ivity	Moisture Content	pH	Acidity	Alka-linity	H_2S or S^{--}	Coal (Coke)	Cl^-	SO_4^{--}	Total
1	-1	-1	0	0	-3	-1	0	-1	0	0	0	-1	0	-8
2	-1	-1	0	0	-3	0	0	-1	0	0	0	-1	0	-7
4	-1	-1	0	0	-3	0	0	-1	0	0	0	0	-2	-8
8	-1	-1	0	0	-3	0	0	-1	0	0	0	0	-1	-7
9	-1	-1	0	0	-3	0	0	-1	0	0	0	0	0	-6
11	-1	-1	0	0	-2	0	0	-1	0	0	0	0	0	-5
13	-1	-1	0	0	-4	-1	0	-1	0	0	0	-1	-3	-12
14	-1	-1	0	0	-2	-1	0	-1	0	0	0	0	0	-6
15	-1	-1	0	0	-2	-1	0	-1	0	0	0	0	0	-6
17	-1	-1	0	0	-2	-1	0	-1	0	0	0	0	0	-6

Classification:

Total of Indexes	Soil Corrosivity
> 0	Practically non-corrosive
From 0 to -4	Moderately corrosive
From -5 to -10	corrosive
< -10	Very corrosive

difference, thereby, inducing a corrosion cell with water as the electrolyte. The build-up of ferric hydroxide at the anode concentrates the further reaction at the site resulting in pitting and growth of tubercles.

Water flowing through a main may contain both corrosion stimulating and inhibiting factors. These factors complicate the simple internal corrosion process. Some of the more important chemical and physical factors that have been discussed by a number of researchers, include:

- pH: The variation in pH, in a range of 5.5-9.0 results in little change in long-term corrosion rates of iron [2]. Increase in pH to a value of 10.0 results in appreciable decrease in the corrosion rate, and a decrease in pH to 4.0 increases the corrosion rate markedly.
- hardness: Hard water decreases corrosion by creating a protective thin film of calcium carbonate, ($CaCO_3$), on the inside pipe wall. On the other hand, soft water accelerates the corrosion process by its mineral contents.
- temperature: A temperature factor, generally, affects reaction rates, gas solubility, and scale formation [1]. An increase in temperature leads to an increase of the diffusion coefficient, and a decrease of the viscosity, as a result the mass transfer coefficient and corrosion rate increases.
- velocity: The effect of velocity on corrosion rates of iron water pipes were investigated by Eliassen and co-workers [15], in both short and long-term studies. The rate of corrosion was shown to increase with increasing velocity flow.
- flow rates: Elevated flow rates allow oxygen to interact more easily with the surface of the conduit, remove protective films, and cause increased corrosion.

Depending on the quantities and combinations of the above factors, water may be aggressive (corrosive), or nonaggressive (noncorrosive). The presence of these factors in a distribution system play an important role in determining the amounts and rates of corrosion in a water distribution system.

In the Calgary case study, the amount of internal corrosion is relatively negligible compared to that of external corrosion. It has been reported also that in the city of Calgary, most of the water pipes are coated with cement-mortar lining. As a result, the original wall thickness of all pipes is simply reduced by the depth of the external corrosion only.

3.4 Survival Analysis of Calgary Mains

An analysis of the pipe breaks has been performed on the data set covering a period of the first twenty years, from the first through the forth break event. A clear distinction between the four groups of pipes can be observed. Figure (3.3) shows that, over a period of twenty years, about 50% of the overall pipes studied, have experienced one failure event, 17% have experienced two break events, 8% have experienced three break events, 7% have experienced four break events, and 18% have experienced more than four break events. The above results reveal that a small number of pipes is responsible for the increasing number of pipe breaks. This implies that it is best to carry out the pipe analysis at the individual level when useful data is available.

Another lifetime analysis has been carried out on a set of water pipes which did not experience any type of break events during their service life. Since corrosion was the most important factor in the deterioration of the water transmission pipes, a life expectancy of pipes was developed based on

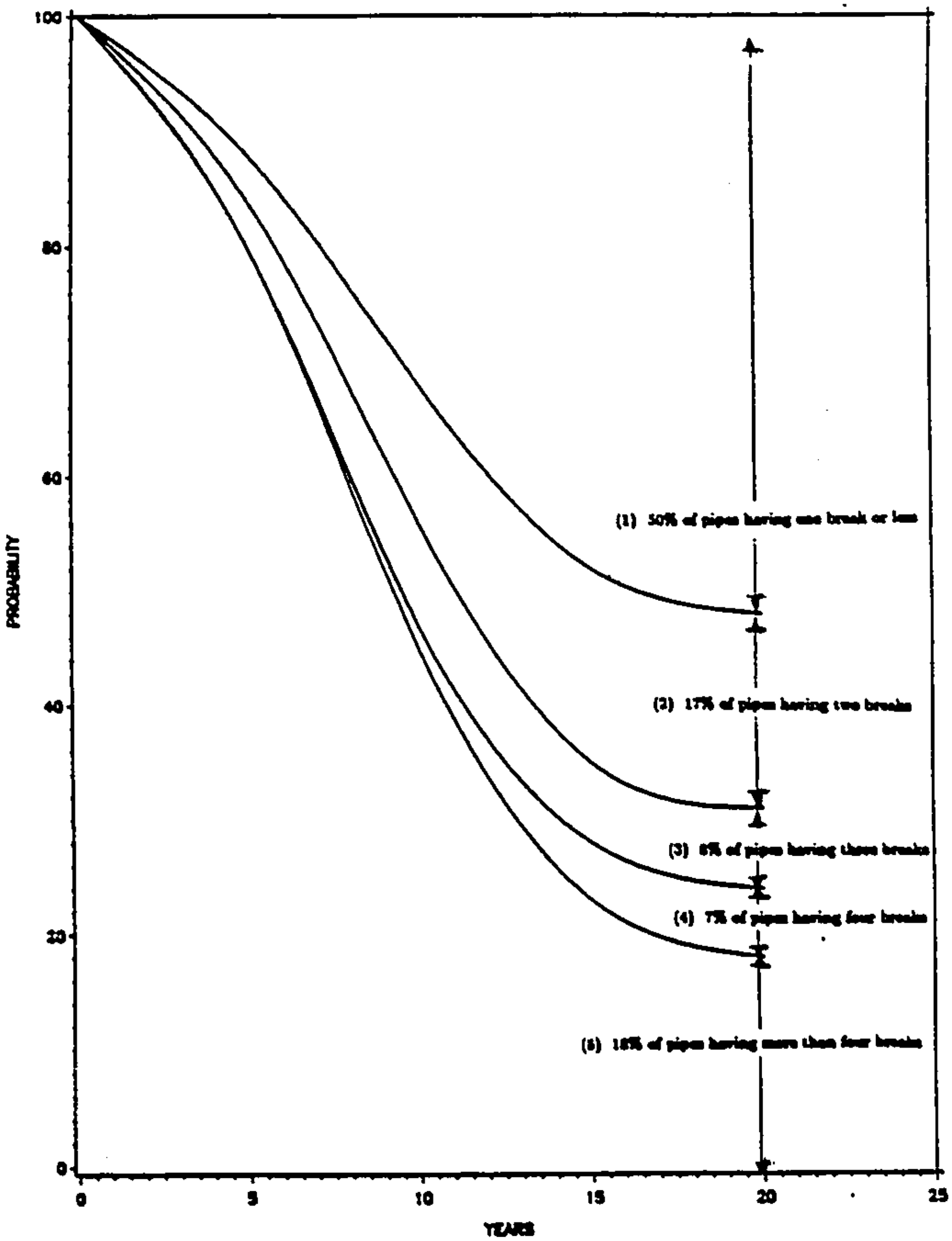

Figure 3.3: Percentage of Pipes Experiencing Failures.

the weight loss of metal and pit depth in the pipe wall, as an indicator of the time elapsed and the expected life to the first breakdown of the pipes. For instance, as can be shown in Figure (3.4), a seven-year old pipe, with no breaks, can expect to have an additional 5.5 years without an event, a fifteen-year old can expected to have an additional 3.3 years before the first event occurs, etc. Beyond the age of twenty-five years, the water pipe is expected to fail in the short time. Finally, it is worth noting that although Figure (3.4) is not adequate for planning purposes. It gives an idea about the behaviour of a number of pipe samples during their lifetime up to the first failure event.

A trend observed in the Calgary data was that when the pipes enter into the breaking stage, the average time, between one break event and the next, becomes increasingly short, Figure (3.5). The above analysis made clear that the age of the water pipe to the first break is very important. The less the age of the water pipe at the first break, the higher the chances for the pipe to break in near future. A possible physical explanation for this can be the fact that a pipe experiencing a first break early in its service life is somehow more defective than a pipe which had a break late in its service life.

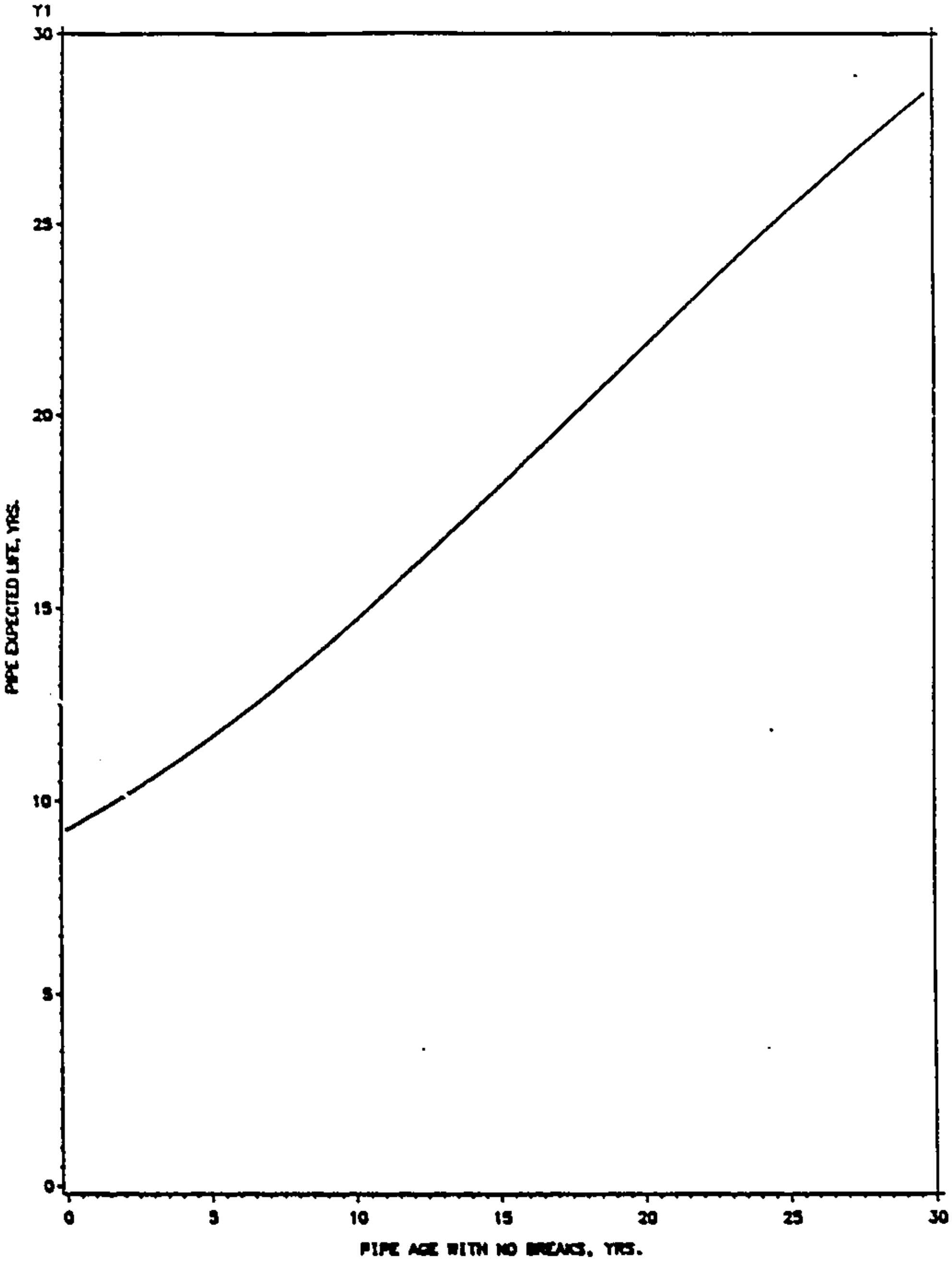

Figure 3.4: Average Life Expectancy to First Break Event.

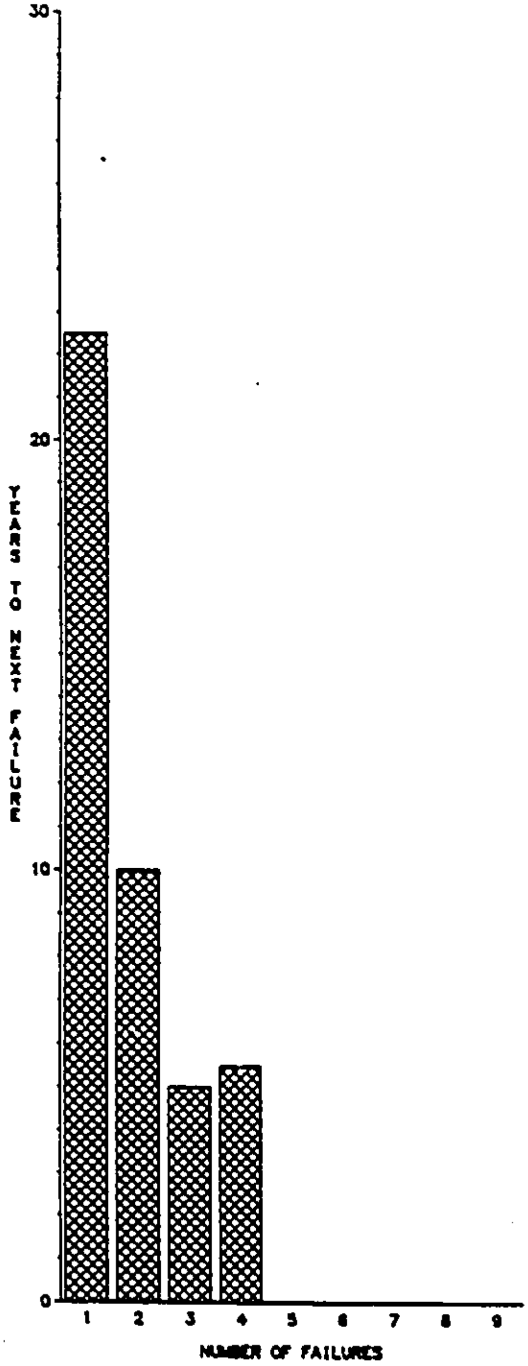

Figure 3.5: Average Time to Next Break Event.

Chapter 4

SEASONALITY PATTERNS AND BREAK-TYPES ANALYSIS

4.1 Seasonality Patterns and Break-Types in Pipe Failures

The analysis performed on the Calgary watermain data did not give detailed distinctions about break-type because the data was not available. A thorough investigation of break type and seasonality patterns in watermain failures could lead to a better understanding of the breaking mechanism, since it would help to focus our attention on particular risk factors and stresses associated with each type of failure.

There is an almost general consensus in the literature [49] that pipe breaks increase during the winter months. In most instances, there is no classification as to whether such seasonality pattern was observed to exist for all pipe sizes. On the other hand, results of the investigation of break type have been very scarce in the literature. The only extensive statistical studies that have investigated the problems of break types and seasonality patterns are those performed by O'Day et al [44], for the cities of Philadelphia and Manhattan, which showed quite similar results. In the Philadelphia study, the following four breaks categories have been investigated: Circumferential breaks, Longitudinal breaks, Hole breaks and Split bell breaks. The findings from this analysis can be summarized as follows:

- Hole breaks are very high in the 1931-1940 mains.
- Split bell breaks are very high in the 1941-1970 mains.
- Circular breaks represent 71% of 6"(150mm) mains, dropping to 34% and 31% for 12"(300mm) and 16"(400mm) mains respectively.
- longitudinal breaks represent 21% of all breaks, varying from 18% for 16"(400mm) to 47% for 10"(250mm) mains.
- split bell breaks represent only 2% of 6"(150mm) mains, 14% of 10"(250mm) mains and 17% of 12"(300mm) mains.

O'Day provides the following structural causes for each break type, Table (4.1). As it is pointed out in his study, the structural causes of failure only indicate the ultimate break cause. It is clear that the condition of the main (e.g., degree of internal and external corrosion), could have been a significant underlying factor. In the O'Day study, there has not been any attempt to examine the statistical correlation between break type and the structural break-causing factors, because of lack of adequate data to describe those factors.

Table 4.1: Main Break Types and Structural Causes, (after O'Day, 1984)

Break Type	Structural Cause(s)
Circumferential	Thermal contraction, beam failure
Longitudinal	Excessive ring load
Hole	Internal pressure blowout
Bell crack	Thermal contraction joint material expansion

The increased break rate during the winter months is well documented in the literature. For example, in the city of Philadelphia [44], the three months of December, January and February accounted for 51% of the main breaks during 1961-1982 period. In the study performed at the city of Buffalo, New York [45], the average break rate during the months of January, February and March is about three times high as the break rate during the fall months and as about twice as high as the break rate during the summer months. It is also observed by the same study that a high break rate also occurs during the month of July, which correlates with the high water demand during the same period. It could be attributed to specific operating characteristics of the system (e.g., increase in internal pressure to meet higher demands). Only in the Manhattan study [44], there has been an attempt to investigate the relation between winter breaks and pipe size. The conclusion was that only pipes smaller or equal to 12"(300mm) in diameter were experiencing increased winter breaks. However no quantitative results are given to show the exact degree of observed seasonalities in failure patterns for each particular pipe diameter below 12"(300mm).

As a general observation, it appears that a detailed analysis of the relationship between break-type and seasonality is currently missing from the literature.

4.1.1 Seasonality Patterns in the Calgary Pipe Failures

The Calgary water distribution system was observed without reference to pipe size. The results of the analysis of the total breaks recorded for Calgary since 1956, indicating the distribution of breaks by month and season is as shown in Table (4.2).

Table 4.2: Seasonal Patterns in the Calgary Water Mains.

December: 11.4%
January: 12.2%
February: 11.3%

Total Winter: 35.1%

March: 11.9%
April: 8.3%
May: 7.4%

Total Spring: 31.5%

June: 5.4%
July: 5.2%
August: 3.6%

Total Summer: 12.9%

September: 4.7%
October: 7.9%
November: 11.5%

Total Fall: 16.2%

A large majority of the pipe breaks in the Calgary water distribution system occurred in winter and part of spring months when the temperature of water and soil is at a minimum. During the months of November to March (cold season), the break rate increases significantly and reaches several times the break rate in the warm season (June to September).

According to Morris [28], as the ground water temperature begins to drop in the fall, various stresses may develop in ferrous pipe. Stress is particularly high when the temperature approaches 4^0C, and the water starts swelling. As the earth temperature drops, it imposes another stress within the pipe. The above stresses and the earth load may cause the initial stress to more than double and eliminate the pipe safety margin. If the pipe is under stress from another source or weakened by corrosion (pitting, graphitation or both), a failure may occur. A peak in the number of failures in the Calgary water main seems to occur when the temperature drops to extreme lows in a few consecutive months (i.e., November, December, January, February and March), Table (4.3).

In order to explain some of the variability in the pipe breaks between one year and the next, it was hypothesized that years with large numbers of breaks were characterized by severe winters and hence large frost penetration and increased loads. While it would have been desirable to correlate the break rate in a year with a maximum frost penetration are not available. Therefore, the average monthly temperature for the period (1956-1980) was used as an indicator of the severity of frost penetration.

An attempt was made to correlate the average monthly break rate versus the average monthly temperature as shown in Figure (4.1). It is apparent from the data that the break rate increases rapidly when the average monthly temperature falls below 0 ^{0}C. The scatter of average monthly break rate versus average monthly temperature is probably due to the large

Table 4.3: Seasonality Pattterns in Breaks of the Calgary Water pipes.

Month of The Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Average Monthly Temp.	-31.8	-27.2	-23.9	-11.1	-3.8	1.7	4.1	2.9	-3.2	-10.7	-22.2	-29.1
Average Monthly Break	61.16	56.28	59.36	41.68	37.16	27.2	26.2	18.12	23.28	39.44	57.28	57.2
Monthly Average Break (%)	12.23	11.26	11.87	8.34	7.43	5.44	5.24	3.62	4.66	7.89	11.46	11.44

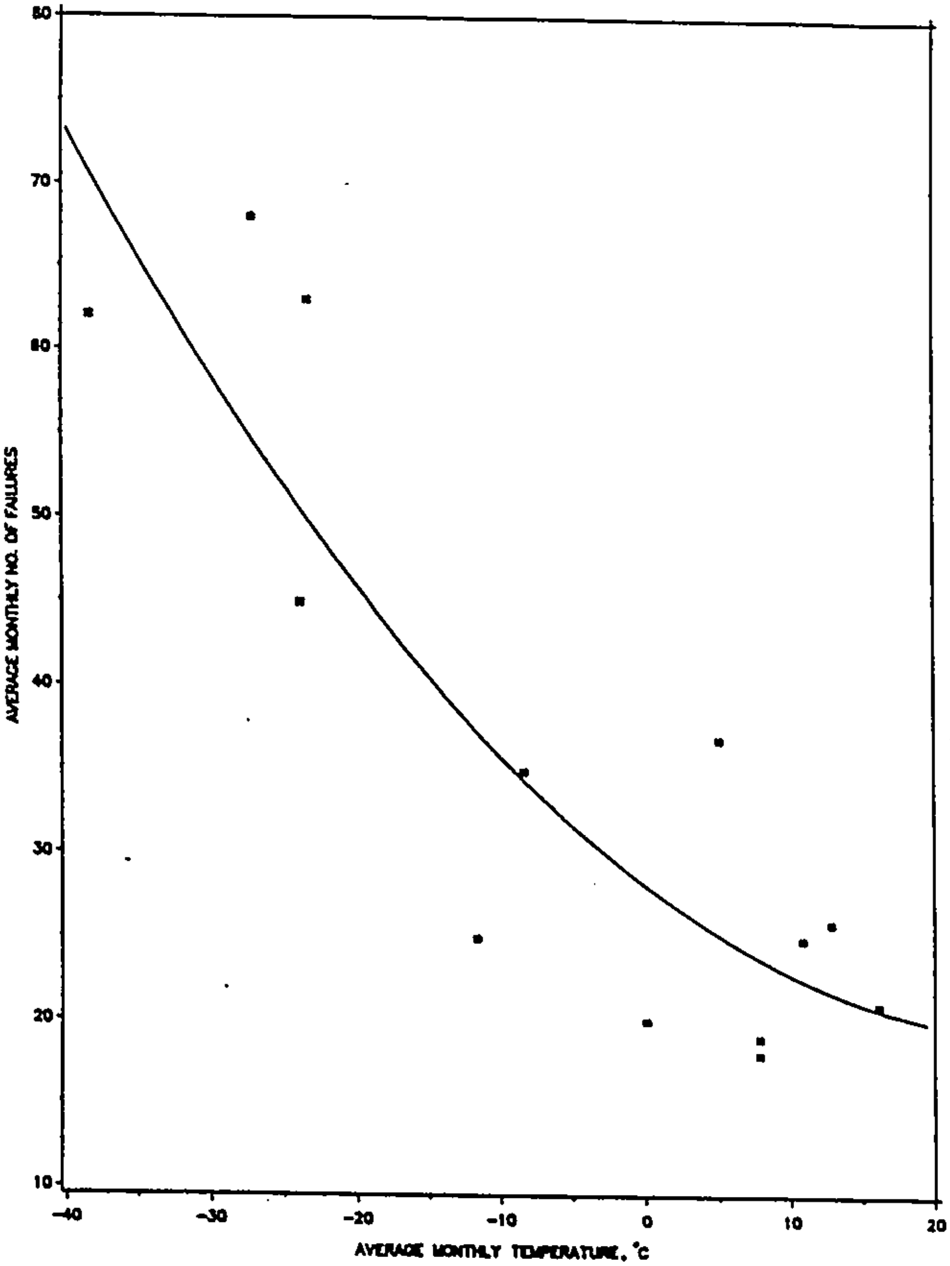

Figure 4.1: Effects of Temperature Variations on Pipe Failures.

variations of daily temperatures.

4.1.2 Break-Type Analysis in the Calgary Water Pipes

A break-type analysis has been performed on a data set obtained from the Calgary Water Works which includes information covering the period 1956-1980 dealing only with break-type. Despite the lack of adequate data about the break date, location of the main, pipe diameter, etc., useful results have been obtained concerning the factors causing each type of break for the overall system. Four major categories of main failures were defined:

- Circumferential (ring-cracks),
- Longitudinal breaks (split pipes),
- Holes in pipes, and
- Joint leaks.

Table (4.4) shows the number and the percentage of breaks associated with each break-type. At the first glance, we observe that about 34.1% of the breaks, in different sizes of pipes, are of the hole type and 55.2% are of the longitudinal and hole types of pipe failures. At the same time, joint leaks, however, do not go beyond 6.7% of the total pipe failures.

Clearly, although information on pipe size is missing from the data sets, which makes the examination of patterns of pipe failure by size and break-type difficult, an analysis has been performed based on break-causing factors, Figure (4.2). It is well known that corrosion is the main underlying cause of the holes, then we could argue that smaller pipes will be affected

Table 4.4: Break Types in the Calgary Water Pipe Failures.

Period	Holes	Circumferential*	Longitudinal** /Holes	Joint Leaks	Total
1956-1980	4252	501	6887	830	12,470
	(34.1%)	(4.0%)	(55.2%)	(6.7%)	(100.0%)

* Cicumferential breaks (ring-cracks),
** Longitudinal breaks (split pipes).

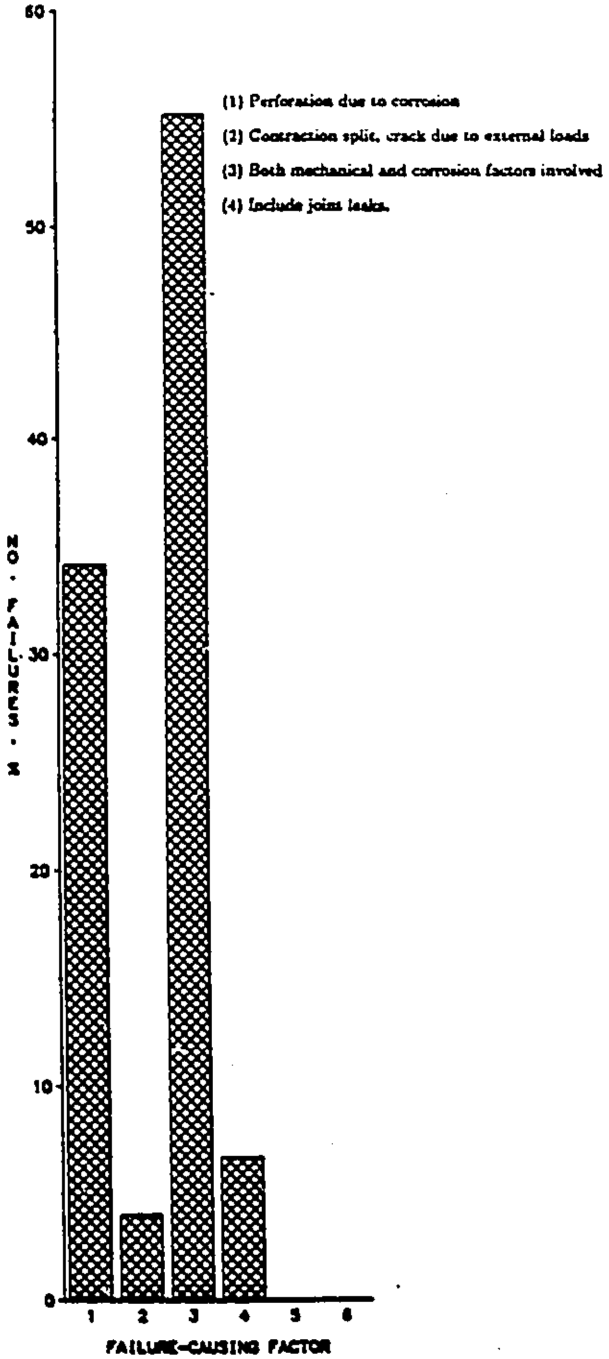

Figure 4.2: Failure Mechanisms in the Calgary Mains.

faster by corrosion than larger pipes since the pipe wall in the former is thinner than in the latter.

In conclusion, the above analysis revealed that, regardless of the pipe sizes in the Calgary system, there is a considerable increase in the pipe failures during the winter months (35.1%) compared to the summer months (12.9%). Such findings are certainly related to weather conditions such as temperature. The lower temperatures affect pipes in two distinct ways :

- Increased tensile stress on pipe is caused by temperature-induced contraction, and
- Increased external stresses are caused by soil moisture expansion from frost penetration.

These tendencies tend to be more severe when the pipes have already been weakened by corrosion over a period of time.

Chapter 5

DEVELOPMENT OF PREDICTIVE MODELS

5.1 Theoretical Background

Regression analysis is used to develop models to forecast the total number of breaks of the pipe over its lifetime and to determine the age to the first break event. Relationships between the dependent variables, such as time to first break and annual break rate, and those independent variables and which rational reasoning indicates are responsible for mains deterioration, are developed. Analysis of the data sets indicates that soil resistivity, soil pH and pipe wall thickness are directly related to the pipe age to the first event. Similarly, the time from the first event, pipe length and percentage of pipe under developed area appear to be the cause of the pipe deterioration. In addition, the regression analysis adopted in the present study permits the comparison of findings with other investigations which use the same statistical procedure.

The independent variables are composed of data sets which may be classified into two categories; data which predict when the first break event occurs and data for those factors reflecting the influence of the environmental conditions after the first break. Predictive models based on regression analysis of the independent variables are developed.

5.2 Model-Building Scheme

Developing a regression model contains three main steps:

- Identification of a suitable class of models that matches the case at hand. The selection of an appropriate form of the model is usually based on experience and past information.
- Calibration of the model which leads to the estimation of its efficient parameters.
- Verification happens after the model is fitted. In this step, the adequacy of the calibrated model has to be tested. If any inadequacy exists, the identification, estimation and verification stages of the model are repeated until a suitable representation is reached.

5.3 Model Identification

The first step in mathematical modeling is model identification. Identification implies that the model has to cover all aspects of the physical system of interest and has sufficient information to select the model that applies. It is assumed that the time to the first break can be represented by a linear model of the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_p X_p \tag{5.1}$$

where
Y= dependent variable as time to first break event.
$X_1, ..., X_p$= independent variables affecting time to first event.
$\beta_0, \beta_1, ..., \beta_p$= unknown coefficients.
While the break rate of the water pipe is assumed to have the form

$$Y = \alpha_0 e^{\alpha_1 X_1} e^{\alpha_2 X_2} ... e^{\alpha_p X_p} \tag{5.2}$$

where
Y= dependent variable as break rate of the water pipe.
$X_1, ..., X_p$= independent variables affecting the destruction of the pipe wall.
$\alpha_0, \alpha_1, ..., \alpha_p$= unknown coefficients.

Thus two types of models are analyzed. The first is a linear model of the independent variables up to the first break, while the second is an exponential model of the independent variables after the first break.

The identification step of model building indicates the representative model which is worthy of the further investigation for a given set of data. After the model is identified, it is subjected to the calibration step of the model building scheme.

5.4 Model Calibration

Having proposed the form of the models to be analyzed, one may proceed with the calibration step of the mathematical modeling. Calibration assures the efficient estimation of the parameters of the proposed models. The calibration procedure used is that of least squares.

That is, the objective function of the calibration is to minimize the sum of squares of the deviations between the computed and the observed values. However, there is no unique statistical procedure for selecting the suitable regression equation. Several procedures based on a goodness-of-fit statistical tests are available and can be used to determine a suitable regression model.

Draper and Smith [13] discuss several procedures for the determination of a suitable model. They recommend the use of stepwise regression. They note that the stepwise regression procedure does not necessarily select the best model but usually selects an acceptable one. The selection procedure chosen in this analysis is the stepwise regression method.

5.5 Stepwise Regression

The procedure of all possible regressions involves the fitting of every possible regression equation. If k independent variables are contained in the proposed model, then 2^k equations will be generated and analyzed to determine the best model. The best model is selected according to the criterion of the verification step of the mathematical modeling procedure. As k becomes large, it is obvious that considerable computations and analyses are required to derive a suitable model from this procedure.

One technique which is widely used and does shorten the selection procedure is that of stepwise regression. Draper and Smith [13] believe that this technique is the best method and have recommended its use. The objective of stepwise regression is to develop a prediction equation relating a dependent (criterion) variable to one or more predictor (independent) variables. Although it is a type of multiple regression analysis, it differs from the commonly used approach in the sense that in addition to calibrating a prediction equation, it uses statistical criteria for selecting which of the available predictor variables will be included in the final regression equation at a given stage or step; the multiple regression technique includes all available variables in the equation and often is plagued by irrational regression coefficients. Stepwise regression usually avoids the irrational coefficients because the statistical criteria that are used in selecting the predictor variables usually eliminate predictor variables that are highly intercorrelated.

The stepwise procedure is very similar to the forward selection procedure in that it consists of building the regression model one variable at a time, by adding at each step the variable that explains the largest amount of the remaining unexplained variation. Using the technique of stepwise regression for selection and rejection of independent variables subjects models to goodness-of-fit tests. These tests actually form part of the verification step in the analysis of the proposed models. Some of the tests used in the stepwise procedure and techniques that are employed in the verification of the proposed models are discussed later in this chapter.

5.6 Model Verification

The adequacy of the identified calibrated model is determined in the verification step of the mathematical modeling scheme. This phase of the modeling procedure attempts to determine in what manner a proposed calibrated model is inadequate, thus possibly leading to appropriate modifications.

5.6.1 Assumptions of the Regression Model

The basic assumptions to be considered in the development of a regression model are:

The general form of a linear regression model is

$$Y_i = \beta_0 + \beta_1 X_1 + ... + \beta_p X_p + \epsilon_i \tag{5.3}$$

where

i= 1, 2,..., n.

ϵ_i= random errors associated with the nth observation.

The first assumption is that the error ϵ is a random variable with a mean of zero and a constant variance. This may be written as

$$E(\epsilon) = 0, \quad V(\epsilon) = \sigma^2 \tag{5.4}$$

The second assumption states that ϵ_i and ϵ_j are not correlated for i not equal to j, so that

$$COV(\epsilon_i, \epsilon_j) = \begin{cases} \sigma^2 & i = j \\ 0 \ \ (i \neq j) & otherwise \end{cases}$$

Thus Y_i and Y_j are uncorrelated for i not equal to j. The final assumption is that the error, ϵ_i, is a normally distributed random variable with a mean of zero and constant variance. That is

$$\epsilon_i \sim N(0, \sigma^2) \tag{5.5}$$

This final assumption implies that ϵ_i are independent and are serially correlated.

5.6.2 The Standard Error of Regression Model

The proposed regression model as given by equation (5.1) is

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_p X_p + \epsilon_i \tag{5.6}$$

The standard error of the regression equation may be estimated by

$$S^2 = \frac{\sum \epsilon_i^2}{(n-p)} = \frac{\sum (Y_i - \hat{Y}_i)^2}{(n-p)} \tag{5.7}$$

where
Y_i= observed value of the dependent variable.
$\hat{Y}_i$= estimated value of the dependent variable.
n= number of observations.
p= number of coefficients of the variables in the model.

5.6.3 The Multiple Coefficient of Determination

An expression for the multiple coefficient of determination, R^2, may be represented by the following formula [13]

$$R^2 = \frac{1-(n-p)S^2}{(n-1)S_Y^2} \tag{5.8}$$

where
S_Y^2= variance of the dependent variable.
S^2, n, p= as previously defined.
The multiple correlation coefficient is defined as the positive square root of the multiple coefficient of determination. The multiple coefficient of determination represents the variation in Y explained by the combined linear influence of the independent variables divided by the total variation in Y. The value of R^2 may vary from 0 to 1 and is analogous to the simple coefficient of determination in the bivariate model.

5.6.4 Significance Test for Regression

All the above assumptions regarding the multiple regression remain valid, that is

1. the expected mean value of the residuals is zero,
2. the variance of the residuals is constant,
3. the independent variables are fixed numbers, and
4. the number of observations exceeds the number of variables.

To test the null hypothesis that β_0 is equal to a hypothetical value of β_i ($H_0 : \beta_i = \beta_0$) versus the alternative hypothesis that β_i is not equal to β_0 ($H_a : \beta_i \neq \beta_0$), one may simply compute the test statistic

$$t = \frac{\hat{\beta}_i - \beta_0}{S_{\hat{\beta}_i}} \tag{5.9}$$

where
$\hat{\beta}_i$= estimated parameters of the regression equation,
β_0, S= as previously defined.
The hypothesis H_0 is rejected if the absolute value of the computed t is greater than a tabulated value of t at the $(1 - \alpha/2)$ level of significance having (n-p) degrees of freedom [17].

The goodness-of-fit of the regression model in general may be assessed through the implementation of a commonly used hypothesis testing procedure. That is, the procedure is to test the null hypothesis that the multiple correlation is zero in the population from which the sample is drawn. The overall null hypothesis H_0:R=0, is equivalent to $H_0 : \beta_1 = \beta_2 = ... = \beta_p = 0$ versus H_1: at least one or more of the β's is not zero. If the null hypothesis is rejected, it implies that one or more of the estimated parameters is different from zero at the respective level of significance. The test statistic used for this general test is

$$F = \frac{R^2/(p-1)}{(1-R^2)(n-p)} = \frac{SS_{REG}/(p-1)}{SS_{RES}/(n-p)} \qquad (5.10)$$

where

SS_{REG}= sum of squares explained by the entire regression model.

SS_{RES}= residuals or unexplained sum of squares of residuals unexplained by the regression.

n, p= as previously defined.

One rejects H_0 if F exceeds the tabular $F_{1-\alpha;p-1;n-p}$ [17].

5.7 Numerical Procedure

Two general categories of models are proposed for analysis. The first is a linear model of the independent variables, while the second is an exponential model of the independent variables. The independent variables to be introduced to the model building scheme are classified into two classes. The first consists of the independent variables that describe the environmental conditions and characteristics of the water pipe from the date of installation to the time of the first break event, while the second one describes the deterioration history of the water pipe after the first break event.

The Statistical Analysis System (SAS) computer package is used in this analysis. It assesses the data and selects the desired variables. The program then proceeds to the stage of model calibration and verification. During this stage, multiple stepwise regression is utilized to calibrate the proposed classes of models.

Appendix D lists and documents the computer program (SAS) used in the analysis.

5.8 Results and Discussion

5.8.1 Independent Variables

The Data set describing the history of the Calgary water mains is used to develop predictive models capable of forecasting the break rates of the water pipes. Table (5.1) lists the variables which are assumed to influence the time to the first break event and the subsequent deterioration rate of the pipe. Soil resistivity, soil pH and pipe wall thickness are considered to affect the pipe conditions during its early service life up to the first break. Table (5.2) lists the simple correlation coefficients for each of the proposed factors with the time to the first failure.

The proposed variables occurring prior to the deterioration phase beginning after the first failure event in their untransformed form, did not appear to have a significant effect on the subsequent break rate of the pipe. An exponential transformation of the independent variables revealed that the proposed predictor variables have a considerable effect on the deterioration rates of the water pipes. However, the correlation matrix in Table (5.3) shows a high intercorrelation among the predictor variables.

5.8.2 Examination of the First Phase Model

Based on the available data, a first phase model is developed which predicts the time elapsed from the date of installation of the water pipe to the time when the first break or failure occurred. The resistivity and the pH of the soil are used to represent the environmental conditions of the Calgary system, while the wall thickness of the pipe reflects the physical characteristics of the water pipes. Through the

Table 5.1: Variables Assumed to Influence the System

Model (1) Y= Time to First Failure, (yrs)	Model (2) Y= Deterioration Rate of Pipe, (br/l/yr)
X_1= Soil resistivity, (Ohm-cm)	X_1= Time from first break, (yrs)
X_2= Soil pH	X_2= Pipe Length, (km)
X_3= Pipe wall thickness, (mm)	X_3= Percentage of pipe under developed area, (%)

```
                        PREDICTION OF TIME TO FIRST FAILURE OF WATER PIPES


CORRELATION MATRIX

                        Y1          X1          X2          X3

                                     1           2           3           4
Y1            1       1.0000
X1            2       0.8778      1.0000
X2            3       0.4684      0.6828      1.0000
X3            4       0.6136      0.6918      0.6045      1.0000
```

Table 5.2: Model 1: Correlation Matrix.

```
                               PREDICTION OF BREAK RATE OF WATER PIPES


CORRELATION MATRIX

                          Y1          X1          X2          X3

                                       1           2           3           4
LOGY1         1       1.0000
X1            2       0.9719      1.0000
X2            3       0.7159      0.7615      1.0000
X3            4       0.9708      0.9228      0.6825      1.0000
```

Table 5.3: Modal 2: Correlation Matrix.

application of the stepwise regression procedure, a selection of the important variables is made. It was observed that high correlations exist among the proposed variables. This serves as a warning of possibly harmful levels of multicollinearity (i.e., when some of the independent variables are intercorrelated among themselves).

The results of the stepwise regression are summarized in Table (5.4). It is seen that the variable which has the greatest effect on the time to the first break event of the water pipe is soil resistivity and the corresponding predictive equation is also given in Table (5.4). The soil pH and the pipe wall thickness variables were both insignificant at the 0.15 significance level for inclusion into a multiple regression model. The regression equation based solely on soil resistivity explains 77% of the variation in the time to first break data and has a standard error of estimate of 0.79 $\times 10^{-3}$ ohm-cm. The computed F statistic is 47.03 for 1 and 13 $(p, n-p-1)$ degrees of freedom. The corresponding critical F value at the 5% level of significance is 4.67. Therefore, the equation is statistically significant. The regression coefficient of the model is considered rational since its sign matches that of the correlation coefficient.

The calibrated model indicates that soil resistivity is very important in the explanation of the time to first failure of the pipe. The resistivity of the soil represents the level of the corrosiveness of the soil. As the resistivity decreases, the soil becomes more and more corrosive and as the resistivity increases, the soil shifts to neutrality. The Calgary soil, as discussed in chapter (3), is mostly characterized by a low resistivity and hence a high corrosiveness, thereby causing an increase in the break rate in metallic pipes. The contribution to the higher break rate is explained by the fact that corrosion weakens the exterior of the pipe wall until it reaches a stage where the pipe cannot withstand the different loads. This finding disagrees with that found

```
               PREDICTION OF TIME TO FIRST FAILURE OF WATER PIPES

 Y1= TIME TO THE FIRST FAILURE OF THE WATER PIPE, YRS.
 X1= RESISTIVITY OF THE SOIL, OHM-CM.
 X2= pH OF THE SOIL.
 X3= WALL THICKNESS OF THE WATER PIPE, MM.

            STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE Y1

NOTE: SLENTRY AND SLSTAY HAVE BEEN SET TO .15 FOR THE STEPWISE TECHNIQUE.

STEP 1    VARIABLE X1 ENTERED           R SQUARE = 0.77061696   C(P) = 2.17696483

                       DF     SUM OF SQUARES   MEAN SQUARE     F      PROB>F

REGRESSION      1       475.80780815    475.80780815  47.03   0.0001
ERROR          14       141.62969185     10.11640656
TOTAL          15       617.43750000

                       B VALUE      STD ERROR      TYPE II SS      F      PROB>F

INTERCEPT     4.19109180
X1            0.00542100     0.00079045     475.80780815  7.03    0.0001

BOUNDS ON CONDITION NUMBER:               1,              1
-----------------------------------------------------------------------------------

NO OTHER VARIABLES MET THE 0.1500 SIGNIFICANCE LEVEL FOR ENTRY INTO THE MODEL.

       SUMMARY OF STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE Y1

                  VARIABLE         NUMBER    PARTIAL      MODEL
STEP   ENTERED    REMOVED      IN      R**2        R**2      C(P)        F         PROB>F

 1       X1                     1     0.7706      0.7706   2.17696   47.0333    0.0001
-----------------------------------------------------------------------------------
```

$$Y1 = 4.1910 + 0.0054X_1$$

Table 5.4: Model 1: Prediction of Time to First Failure.

by Mark et al [25] in their study of the New Haven system. Mark et al [25] found that corrosion does not contribute severely in the deterioration of the New Haven system. A possible explanation for this could be the fact that highly corrosive soil(i.e., low resistivity) had indeed contributed significantly in making the Calgary system much more prone to failure than the New Haven. It could be that the soil conditions were much more corrosive in Calgary, while in New Haven the soil corrosion did not pose severe problems. It is evident that the soil resistivity as a predictor does not fully explain the variation in the first phase model. The reason is that the soil resistivity can only give limited information concerning the effect of corrosion on pipe deterioration. In addition, such a variable can not reflect all the degrees of corrosion as argued in chapter (3).

5.8.3 Examination of the Second Phase Model

The second phase model represents the forecasting of the deterioration rates of the water pipes. Variables affecting the deterioration rate of the pipe are considered to be the time from first break event, the pipe length and the percentage of pipe under developed areas. The stepwise regression procedure is used in the calibration and verification of the model. It appears that only the time from first failure variable explains significantly the variation in the deterioration rate of the pipe and the corresponding predictive equation is given in Table (5.5) along with other results from the stepwise regression.

The correlation coefficient for the model is 0.974, representing 94.2% of the total variation in the deterioration rate of the water pipe data. The computed F statistic is 196.28 for 1 and 11 $(p, n-p-1)$ degrees of freedom and the critical F value at the 5% level of significance is 4.84. Therefore, the equation is statistically significant. Regarding

```
                         PREDICTION OF BREAK RATE OF WATER PIPES

Y1= BREAK RATE OF THE WATER PIPE PER YEAR PER SEGMENT OF LENGTH.
X1= TIME ELAPSED SINCE THE FIRST FAILURE OF THE WATER PIPE, YRS.
X2= LENGTH OF THE SEGMENT OF THE WATER PIPE, KM.
X3= PERCENTAGE OF THE WATER PIPE UNDER DEVELOPED AREA, %.


            STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE Y1

NOTE: SLENTRY AND SLSTAY HAVE BEEN SET TO .15 FOR THE STEPWISE TECHNIQUE.

STEP 1   VARIABLE X1 ENTERED      R SQUARE = 0.94238420     C(P) = 1.68326593

                      DF          SUM OF SQUARES     MEAN SQUARE      F        PROB>F

REGRESSION      1            43.41508709       43.41508709    196.28    0.0001
ERROR          12             2.65432588        0.22119382
TOTAL          13            46.06941297

                                B VALUE      STD ERROR     TYPE II SS       F        PROB>F

INTERCEPT           1.05697322
X1                  0.43684728    0.03118141     43.41508709     196.28    0.0001

BOUNDS ON CONDITION NUMBER:              1,             1
-----------------------------------------------------------------------------------

NO OTHER VARIABLES MET THE 0.1500 SIGNIFICANCE LEVEL FOR ENTRY INTO THE MODEL.

   SUMMARY OF STEPWISE REGRESSION PROCEDURE FOR DEPENDENT VARIABLE Y1

                  VARIABLE           NUMBER   PARTIAL    MODEL
STEP   ENTERED    REMOVED      IN     R**2       R**2      C(P)         F          PROB>F

  1      X1                    1     0.9424     0.9424   1.68327   196.2762     0.0001
-----------------------------------------------------------------------------------
```

$$Y1 = 1.0569e^{0.4368 X_1}$$

Table 5.5: Model 2: Prediction of Break Rate of Water pipes.

the coefficient sign, it is considered rational as it matches the sign of the variable correlation coefficient.

Similar to the first phase model, high intercorrelations are observed among the independent variables, which indicates a possible presence of multicollinearity. In the second phase model, the parameter of the time from first break event does significantly explain the variation in the deterioration rate of the water pipe. It is shown in chapter (3) that the shorter the time from the first failure of the pipe to the second, the higher chances for the pipe to break in the near future. A possible explanation can be the fact that a pipe experiencing a second break early in its life is less structurally strong than a pipe which for a second break comes late in its life. Or, it might be that some unknown causing factors are present and are more severe in the case of a pipe that broke many times in its life. At any rate, a short time from the first break to the second tends to indicate a strong correlation between the first and the coming break as well as the time beyond the first failure of the pipe. Figure (5.1) represents a comparison of predicted break events with actual ones.

It is difficult to evaluate the reliability of data set. The reason is that there was no clear description of the accuracy of the instruments used in the survey and the methods followed in the collection of samples. Despite that, the results have shown that the resistivity of the Calgary soil and the time elapsed from the first failure event are significant in the description of the history of breaks in the Calgary water distribution system.

In the early age of the water pipe, it appears that the external corrosion played a great role in the weakening of the pipe wall. As a result, the water pipe has lost its strength and became prone to failures. Thus, in the first stage of the pipe's life, the soil conditions were more critical to the pipe deterioration than any other factors (envi-

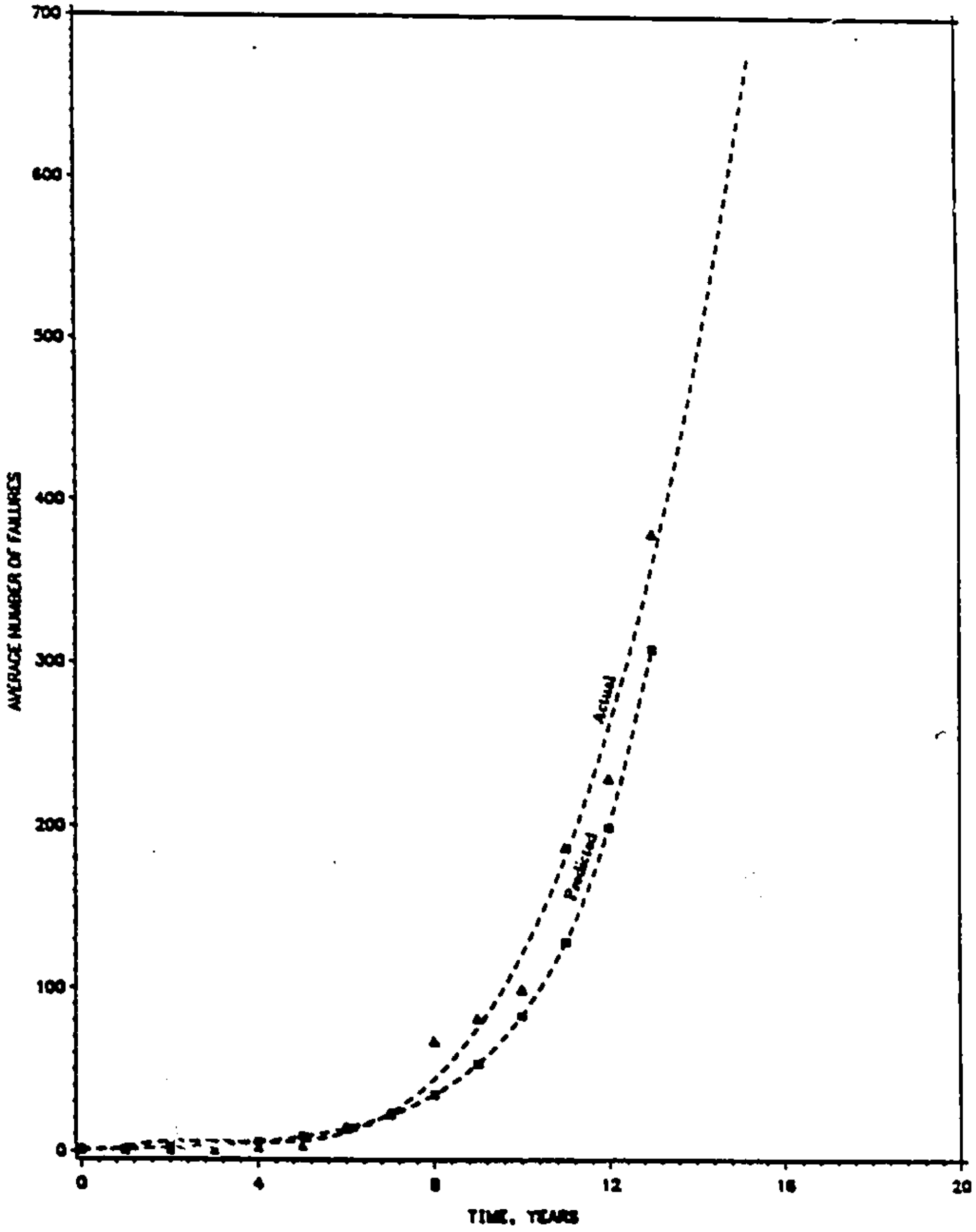

Figure 5.1: History of the Calgary Water Main Failures.

ronmental conditions and pipe characteristics for instance). While in the second stage of the pipe's life, each successive break tends to take place faster than the one before. That is, the number of the pipe failures were increasing exponentially. In the Calgary case, it is observed that the growth rate of the water pipes was relatively high (compared to previous investigations [40, 49, 50]). This could be attributed to the fact that the data samples were taken from areas severely affected by corrosion. As a result, the developed models of this study cannot be applied to the overall water system as one.

Before major repair/replacement costs are incurred due to pipe breaks, it is important to protect the water pipe suitably. Cathodic protection and coating should be carefully installed in order to delay the pipe defects and maintain its reliability. But in general, the type of the pipe protection could vary depending on the factors that cause the pipe failures and the cost of the appropriate action for keeping the structural integrity of the water pipe.

Chapter 6

REPLACEMENT AND REPAIR DECISIONS

6.1 Introduction

The current state of deterioration of many water distribution systems raises serious questions regarding the optimal repair and replacement strategies that need to be implemented. The criteria used in making such maintenance decisions are classified in the following two broad categories:

1. Economic criteria, and
2. Reliability service criteria.

The economic criteria involved in the repair and replacement decisions take into account the costs of the break repairs and the costs for the replacement of pipe segments. One important objective becomes the minimization of expected future repair and replacement costs of a deteriorating pipeline.

This can be achieved by deriving an optimal replacement time for each particular pipe based on predictions about the evolution of its failure pattern. The problem of deciding which pipes in the system to replace and when, based on economic efficiency criteria, becomes more complex when economies of scale can be realized depending on the size of the contracts chosen for replacement.

The reliability criteria involved in the repair/replacement decision usually include the following considerations:

- Inconvenience to customers caused by interruptions in service due to breaks.
- Potential difficulties for meeting fire flow demands in various parts of the network.
- Potential damages caused by breaks due to flooding of streets, basements, and subway stations, and
- Disruptions in traffic and other underground pipelines.

Economic considerations can be involved here too, because of the potential liability of the utility for the associated damages.

6.2 Repair Versus Replacement Decision

When a pipe starts experiencing breaks, the question arises as to whether it is more economical to let breaks occur with the associated repair costs or to replace the pipe at some point in time and to dramatically reduce the chances for breakage in the near future. The replacement action should not necessarily involve the whole pipe length, but sections of the pipe, depending on the available information about the distribution of the break causing-factors and the integrity of the pipe. The cost of repairing a break is usually small compared to the replacement costs. Thus, if only these types of costs are involved in economic analysis, it must be expected that only the severely weakened pipes with frequent breaks will become candidates for replacement within a reasonable (10 - 15 years) time horizon [5]. But since there would also be "social" costs associated with breaks and a potential liability for the water utility, replacement of a pipe could very well in many cases be based solely on reliability criteria. No matter what the chosen criteria might be, an important part of the information needed for making such decisions is the expected evolution of failures associated with each individual pipe or group of pipes with relatively similar failure histories.

6.3 Theoretical Background of Replacement Timing

According to previous developed analyses, the number of break events in a given section of a single pipe, group of pipes with similar characteristics or a whole region of a network, can be described by the following equation, [40].

$$N(t) = A_1 e^{A_2(t-t_0)}, \quad if\ (t > t_0) \tag{6.1}$$

Where

N(t) = number of breaks per pipe section per year,

A_1 = number of breaks at base time t_0,

A_2 = growth rate coefficient, ($\frac{1}{year}$),

t_0 = base time, years, and

t = time, years.

As the number of events per year increases, so does the cost of responding to them. If the cost of repairing a break C_b, expressed in constant dollars, is assumed to be constant with time, then the cost of repairing the breaks in a given length of pipe in the future year t is

$$C_m(t) = C_b N(t) \tag{6.2}$$

or

$$C_m(t) = C_b A_1 e^{A_2(t-t_0)} \tag{6.3}$$

If the present year is denoted by t_p, and the discount rate is R, then the present value of this repair cost is simply

$$\frac{C_m(t)}{(1+R)^{(t-t_p)}} \tag{6.4}$$

Denote by t_r the year in which the pipe will be replaced. The present value of all maintenance costs from the present year t_p to the year t_r is

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{(t-t_p)}} \tag{6.5}$$

or

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_b A_1 e^{A_2(t-t_0)}}{(1+R)^{(t-t_p)}} \tag{6.6}$$

The cost for replacing a section of pipe, expressed in the same constant dollars as C_b, is C_r. The present value in year t_p of replacing a section of pipe in year t_r is therefore

$$P_r(t_r) = \frac{C_r}{(1+R)^{(t_r-t_p)}} \tag{6.7}$$

$P_m(t_r)$ is an increasing function of t_r, because every additional year that passes before the pipe is replaced is an a additional term in equation (6.5). On the other hand, $P_r(t_r)$ decreases with t_r because it is assumed that C_r is constant, whereas the denominator increases with t_r.

The optimal timing for replacement in that year for which the total cost is

$$P_t(t_r) = P_m(t_r) + P_r(t_r) \tag{6.8}$$

or

$$P_t(t_r) = \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{(t-t_p)}} + \frac{C_r}{(1+R)^{(t_r-t_p)}} \tag{6.9}$$

is a minimum. Therefore determining the value of t_r, which minimizes equation (6.9)

$$Min_{t_r}[P_t(t_r)] = Min_{t_r}[\sum_{t=t_p}^{t_r} \frac{C_b A_1 e^{A_2(t-t_0)}}{(1+R)^{(t-t_p)}} + \frac{C_r}{(1+R)^{(t_r-t_p)}}] \tag{6.10}$$

Differentiating with respect to t_r, setting equal to zero, solving, we get the optimal value

$$t_r^* = t_0 + \frac{1}{A_2} ln[\frac{ln(1+R)C_r}{A_1 C_b}] \tag{6.11}$$

The base year t_0 used in developing the equation (6.1) has no influence on the solution. This can be seen by observing that the number of breaks at some other year, say the present year t_p, is

$$N(t_p) = A_1 e^{A_2(t_p-t_0)} \tag{6.12}$$

and therefore, for any future year t

$$N(t) = A_1 e^{A_2(t-t_0)} \tag{6.13}$$

or

$$N(t) = A_1 e^{A_2(t-t_p+t_p-t_0)} \tag{6.14}$$

or

$$N(t) = [A_1 e^{A_2(t_p - t_0)}] e^{A_2(t - t_p)} \tag{6.15}$$

Finally

$$N(t) = N(t_p) e^{A_2(t - t_p)} \tag{6.16}$$

Thus equation (6.6) can be written

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_b N(t_p) e^{A_2(t-t_p)}}{(1+R)^{(t-t_p)}} \tag{6.17}$$

Introducing this expression into equation (6.10), differentiating, setting equal to zero, and solving for t_r^* leads to

$$t_r^* = t_p + \frac{1}{A_2} ln[\frac{ln(1+R)C_r}{A_1 C_b}] \tag{6.18}$$

This expression gives the same results as equation (6.11), demonstrating that the arbitrarily selected base year t_0 has no effect on the result.

6.4 Cost for Repair and Replacement

The discussion presented in this section involves the use of repair and replacement costs for water mains. Such costs are not the same for each pipe. They vary primarily with size and break-type. Thus, when any of the derived formulas for economic analysis is applied, the appropriate costs for each particular case must be substituted.

Shamir and Howard [40] assumed a repair cost per break equal to $1000 per break with a range of $500 to $2000. No detailed discussion is given of how they arrived at those values. In the Manhattan, New York study [44], the direct costs to the Water Supply Bureau were assumed equal to $7323 including eleven person-days of Water Bureau staff time per break. According to the previous study, the average settlement was roughly $1000 per break (1980 dollars). Clark et al [5] reported that the average cost for break repairs ranged from $1170 to $1760 per break for the Cincinnati, Ohio, Water Works (1975 dollars). Walski and Pelliccia [49] developed synthetic cost function for breaks by calculating the costs of individual items involved in the break repair (labor and material costs). They included the following elements:

$$\text{Cost of repair} = \text{Crew} + \text{Equipment} + \text{Repaving}$$

Table (6.1) shows the estimated total costs by pipe diameter for the cities of Binghamton and Buffalo in New York State. It is argued in that study that the Buffalo costs are more representative of typical repair costs in an urban area.

Breaks are also a function of break-type, which apparently has not been taken into account in the previously mentioned studies. Circumferential breaks can be repaired with a clamp while split bell and longitudinal breaks require that part of the pipe be cut out and replaced. King [21] presented estimated costs from 416 breaks for the City of Philadelphia that occurred during the period of 1975 to 1981. The results are shown in Table (6.2).

Replacement (relaying) of pipes with new ones in urban areas represents significantly higher costs than laying new pipes for the first time in undeveloped areas. Pipe replacement costs involve all costs paid to the project contractors. They include the following items [47]:

- Excavation,
- Abandoning existing pipe,

Table 6.1: Pipe Break Repair Costs (1983 Dollars)[47]

Pipe Diameter, (in)	Binghamton Costs, ($)	Buffalo Costs, ($)
4	718	1,455
6	786	1,558
8	839	1,679
10	896	1,780
12	920	1,872
16	1,266	2,315
18	1,305	-
20	1,415	2,434
24	1,770	2,755
30	-	3,289
36	-	3,485
48	-	4,107

Table 6.2: Pipe Break Repair Cost by Type of Break (1983 Dollars)[47]

Pipe Diameter, (in.)	Cost for Indicated Type of Break, ($)		
	Circumferential	Split	Longitudinal
6	930	975	1,058
8	895	1,202	1,053
10	1,149	1,380	1,611
12	1,362	1,087	2,516
16-48	2,237	3,904	5,620

- Laying new pipe,
- Reconnecting services,
- Pressure testing,
- Disinfection,
- Backfilling and repaving.

For the city of Philadelphia, cost information was available as actual price per foot of pipe averaged over all projects in a single year and not on a project-by-project basis.

In the New York city study [34], costs of pipe relaying included the following items:

- Protection and maintenance of traffic,
- Removal of pavement,
- Excavation,
- Removal of existing mains,
- Furnishing and replacing new pipe,
- Backfilling using material from excavation removal and replacement of hydrants and valves.

Costs of pipe replacement were also estimated for the city of Buffalo [45]. In general, the differences in costs between the New York and Buffalo estimates can be attributed to lower labor and excavation costs in Buffalo.

It must be pointed out that replacement costs will also vary depending on the size of the contracts. It might also be more economical if replacement of pipes is done "in house" by the water utility rather than using outside contractors. However no accurate data were available to support this argument.

In conclusion, for a given location, repair and replacement costs depend directly on the pipe size and break-type. Costs also vary according to the event location. For example, the costs depend upon whether failure occurs in developed or undeveloped areas. In the Calgary case study, a cost for repair C_b= \$1000 per break and a cost for replacement C_r= \$70,000 per year and per a link of pipe are considered for illustrative purposes as given by Shamir and Howard [40].

Since many replacement decisions, particularly for severely deteriorated pipes, will give a high priority to reliability considerations, the following categories of failure impact can be identified in addition to the break repair costs:

- Service disruption: Disruption of service will be of varying importance depending on the type of land use covering the pipe (residential, industrial, commercial, etc.). If a failure occurs in a distribution main of great importance in the hydraulic network, then a probable disruption in service may extend well beyond the local point of failure. For this reason, a parameter describing the land uses must be included in the analysis and modelling of water main deterioration.
- Urban disruption: Urban disruption includes impacts on various activities. Water main failures could result in traffic disruptions because of street flooding, street damage and excavation within the street during repair. The level of impact will probably depend on traffic volume and also the expected duration of traffic disruption. Table (6.3) shows the estimated time to repair breaks by pipe diameter and break-type [30].

  Other types of urban disruption may include flooding of basements and subway stations. Other underground utilities, particularly power and natural gas distribution, could also be threatened by water main failures.

Table 6.3: Time to Repair Breaks (in hrs.)[47]

Pipe Diameter, (in)	Philadelphia			Binghamton
	Circular	Split Bell	Longitudinal	
6	8.7	6.9	10.0	11
8	7.7	10.6	9.5	12
10	10.2	13.2	13.2	12
12	12.2	9.4	20.6	13
16-48	21.9	29.7	47.1	-
16	-	-	-	14
20	-	-	-	15
24	-	-	-	16

6.5 Thermoplastic Water Mains

Plastic water pipes have been on the market sometime and have demonstrated their ability to compete favorably with the traditional water mains particularly the metallic ones. Acceptance of plastic pipes for water distribution systems by water utilities has been greater than originally predicted, and this can be attributed to the fact that the product's advantage outweigh some minor disadvantages.

6.5.1 Superior Properties

The technical advantages of thermoplastic pipes are as follows:

- Noncorrosiveness: Plastic materials are essentially noncorrosive in nature and therefore do not corrode and form oxides as do metallic pipes. The most significant and obvious benefit to be derived from the use of plastic pipes is the fact that these water pipes are considerably more hygienic than their metallic counterparts.
- Smooth Internal Molded Surface: Plastic pipes provide high resistance to the buildup of mineral deposits normally found in metallic pipes. The rough surface finish inherent in casting encourages the buildup of these deposits to adhere. Once this initial deposit begins to form, it is rapidly accelerated. On the other hand, plastic pipes remain smooth and thus have less internal resistance to the flow.
- High Specific Strength: The high specific strength is defined as the strength-to-weight ratio of the pipe. Most engineering thermoplastics have high specific strength that are equal and, in several cases, considerably higher than many common metals including cast iron, a commonly used pipe material. When these

thermoplastics are reinforced by the addition of fiber glass or other fibers such as graphite or polyesters, their strength-to-weight ratio is further enhanced.

- Light weight: Because of the light weight of plastics compared to metals, firstly, plastic pipes are much more easier to handle, thereby, providing for more efficient installation of the pipes. Secondly, when installed in systems, the pipe weight that must be supported in several types of installations is considerably less. Thirdly, the shipping cost of the plastic pipes is considerably lower.

6.5.2 Low Initial and Maintenance Costs

Although the advantages cited in the first category are significant, the economic advantages are of equal, if not greater, importance.
The lower initial cost can be attributed to a combination of two factors:

- Lower material cost: Compared to metal cost, the net material cost of plastic pipe is somewhat less because there is a large difference in densities of the two materials. The weight of an equal volume of plastic is approximately one sixth that of the metal.
- Labor cost: Lower labor costs contribute to a substantial portion of the lower initial cost of plastic pipe, and also plays an important part in reducing maintenance cost. The reason for the decrease in the labor cost lies in the ability of plastic molding processes to produce highly accurate parts which are difficult to achieve in metallic pipes. The ease of assembly and disassembly saves time and reduces, in general, the maintenance cost.

6.6 Sensitivity Analysis

Sensitivity is the relative magnitude of the change in one or more elements of a problem required to change the decision. An analysis of the sensitivity of a decision to the various parameters highlights important and significant aspects of a problem [30]. In the Calgary case study for instance, one might be concerned about discovering the key parameters influencing the optimal time for replacing a specific pipe or a group of pipes with similar environmental conditions. Sensitivity analysis might indicate that the optimal time for replacing, t_r^*, is more sensitive to some elements more than others. Under these circumstances, one should place greater emphasis on improving those elements having greater impact on the optimal timing for replacement of water pipes.

The sensitivity of t_r^* to variations in each of the parameters in equation (6.11) is obtained by differentiating t_r^* with respect to A_1, A_2, C_b, C_r and R.

$$\frac{\partial t_r^*}{\partial A_2} = \frac{-1}{A_2^2} ln[\frac{ln(1+R)C_r}{A_1 C_b}] \tag{6.19}$$

$$\frac{\partial t_r^*}{\partial R} = \frac{1}{A_2(1+R)ln(1+R)} \tag{6.20}$$

$$\frac{\partial t_r^*}{\partial A_1} = \frac{-1}{A_1 A_2} \tag{6.21}$$

$$\frac{\partial t_r^*}{\partial C_b} = \frac{-1}{A_2 C_b} \tag{6.22}$$

$$\frac{\partial t_r^*}{\partial C_r} = \frac{1}{A_2 C_r} \tag{6.23}$$

By differentiating the optimal time for replacement, t_r^*, with respect to each parameter mentioned above holding the others being at their typical values.

$$\frac{\partial t_r^*}{\partial A_2} = -9.657 \tag{6.24}$$

$$\partial A_2 = -0.103 \partial t_r^* \tag{6.25}$$

This means that the optimal time for replacement, t_r^*, will decrease by one year for an increase of 0.103 in the growth rate coefficient, A_2.

$$\frac{\partial t_r^*}{\partial R} = 21.836 \tag{6.26}$$

$$\partial R = 0.045 \partial t_r^* \tag{6.27}$$

This result indicates that the optimal time for replacement, t_r^* , will increase by one year for an increase of 4.5% in the discount rate, R.

$$\frac{\partial t_r^*}{\partial A_1} = -2.166 \tag{6.28}$$

$$\partial A_1 = -0.461 \partial t_r^* \tag{6.29}$$

The optimal time for replacement, t_r^*, will decrease by one year for an increase of 0.461 in the initial number of breaks, A_1.

$$\frac{\partial t_r^*}{\partial C_b} = -0.0023 \tag{6.30}$$

$$\partial C_b = -434.782 \partial t_r^* \tag{6.31}$$

This is an indication of a decrease in the optimal time for replacement, t_r^*, by one year for an increase of \$434.782 in the cost of repair, C_b.

$$\frac{\partial t_r^*}{\partial C_r} = 3.269 \times 10^{-5} \tag{6.32}$$

$$\partial C_r = 0.306 \times 10^5 \partial t_r^* \tag{6.33}$$

The optimal time for replacement, t_r^*, will decrease by one year for an increase of \$3.060 × 10^4 in the costs of replacement, C_r.

The value of the optimal time for replacing, t_r^*, is critically dependent on the value of C_r. The value of t_r^* could highly vary depending on the cost of the appropriate remedial action for restoring the structural integrity of the pipe.

6.7 Discussion of Results and Application

It has been pointed out in the previous failure history analysis of the Calgary system that the number of breaks was increasing exponentially with time. This increase in the pipe deterioration leads to an increase in the expenses of the operation and maintenance. Therefore, water utilities more than ever need wise decisions as to whether to replace or to keep on repairing the pipes. To illustrate some of decisions that water managers will be required to make, a trade-off analysis between repair and replacement costs is presented.

In any system, the break rate can be estimated when the predictive equations are given. Then an analysis, based on economic and reliability considerations can lead to a replacement/repair decision. In general, the pipe should be replaced before the expenses spent on repairs exceed the value of replacing the main.

Figures 1-10 (Appendix C) show the results of the economic analysis based on data of the city of Calgary. Table (6.4) contains typical values from the data base used to estimate the parameters in the predictive equations and economic data. Figures 1-4 (Appendix C) represent the same economic data of water pipes with different failure histories. They contain curves which show:

1. Value of all future replacement costs, equation (6.2), as function of the replacement year.
2. Value of repairing the pipe , equation (6.4), as function of the replacement year.
3. Sum of the two previous ones.
4. Optimal year for replacement as computed from equation (6.11).

Figures 1-4 (Appendix C) represent the same economic data of water pipes with different failure histories. It is observed that the optimal time for replacement dates are slightly different.

- The pipe having the higher growth coefficient, A_2, experiences a higher rate of increase in breaks and should therefore be replaced early.
- An increase in the discount rate, R, tends to shift the optimal replacement date to the right and results in a relative delay in the replacement dates. Figures 2-4 (Appendix C) show that the lower discount rates produce a more sharply defined optimal replacement date, that is closer to the present. Table (6.5) summarizes those results.

In summary, a number of observations can be made:

1. The optimal time for replacement, t_r^*, increases as the discount rate R increases. Quantitatively, for a one year increase in t_r^*, R increases on the average by 2.4% in the range of values studied.
2. The optimal replacement time, t_r^*, is more sensitive to the change in the cost of replacement, C_r, than to the change in the other parameters.

Table 6.4: Typical Values for Pipe Parameters[3]

Parameter	Value
A_1(Initial number of breaks)	1.0569 (br/l).
A_2(Growth rate coefficient)	0.4368 (1/yr).
R(Discount rate)	10%
C_r(Replacement cost)	$70000 (1/l).
C_b(Reapir cost)	$1000 (1/br).
X_1(Soil resistivity)	760.00 (Ohm-cm).
$Y_1 = t_0$(Base time)	8.0 (yrs).

Table 11: Optimal Time for Replacement

Case number	A_1,(br/l)	A_2,(1/yr)	R,(%)	t_r^*,(yrs)
1	1.0569	0.4805	10	13.0
2	1.0569	0.4368	10	14.4
3	1.0569	0.4368	7	13.6
4	1.0569	0.4368	4	12.0

Equation (6.18) gives the optimal replacement time for the replacement of water pipes

$$t_r^* = t_0 + \frac{1}{A_2} ln[\frac{ln(1+R)C_r}{A_1 C_b}] \tag{6.34}$$

where,

t_r^*= optimal time for replacement (measured from first break), years,
t_0= base time, here t_0=0 years,
A_2= growth rate, 1/year,
R= discount rate, %,
C_r= cost for replacement of a pipe link, \$,
C_b= cost per individual repair, \$, and
A_1= number of breaks at the base time t_0,

The inverse of the growth rate coefficient, $(1/A_2)$, can be expressed in terms of the number of breaks, A_1, at the base time, t_0. Setting the base time, t_0=0 years, the equation (6.38) will be

$$t_r^* = \frac{1}{A_2} ln[\frac{ln(1+R)C_r}{A_1 C_b}] \tag{6.35}$$

If the values of the parameters R, and (C_r/C_b) are known, then equation (6.39) can be written as follows

$$t_r^* = \frac{1}{A_2} ln[\frac{k}{A_1}] \tag{6.36}$$

where

$$k = ln[\frac{(1+R)C_r}{C_b}] \tag{6.37}$$

and finally,

$$\frac{1}{A_2} = t_r^* \; ln[\frac{A_1}{k}] \tag{6.38}$$

In Figures 5-10 (Appendix C), values of t_r^*= 5, 8, 11, 14 years are arbitrarily chosen. Using a value for A_1, a point can be plotted on the each the graphs. If this point falls below the curve representing the current year, the pipe should be replaced. If it falls on the curve, this means that the pipe has reached its optimal time and it is better to be replaced before the repair costs overcome the replacement costs. If the point finally, falls above the optimal time curve, replacement of the water pipe is still early because the replacement costs of the pipe are definitely more costly than replacing it later than the optimal date suggested by the analysis. If the data used in the analysis are in doubt, Shamir [40] suggested that it might be advisable to concentrate on repair rather than renewals.

Some observations can be made:

1. Generally speaking, as we consider pipes with low replacement-repair ratio ($\frac{C_r}{C_b}$), the chances of replacement decrease, particularly at high values of A_1 as shown in Figures 5-8 (Appendix C). For the above consideration, the discount rate R was held constant.
2. In the second case Figures 9-10 (Appendix C), As A_1 increases, the chances of replacement are getting higher particularly at high values of R. That is, the optimal replacement is becoming shorter and shorter. The replacement-repair ratio, ($\frac{C_r}{C_b}$), is held constant.

The purpose of developing these charts is for planning repair and replacement strategies. It must be born in mind that only pipes having their data analyzed can be used with these charts, that is, they must have their growth rate coefficients, A_2, and initial number of breaks, A_1, determined by up-to-date field data. However, the use of these charts is helpful primarily in determining future conditions of larger transmission mains.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 Conclusions

When the research of this thesis began, the ultimate goal was to develop a method to analyze break records and develop a formula for predicting breaks and making maintenance/replacement decisions. Water utilities would thus be able to evaluate the useful-life of their transmission mains and use this as a means of scheduling replacement before major costs are incurred due to pipe breaks. Although the goal was not reached in its entirety, a number of conclusions can be drawn:

1. Statistical data analysis showed that an important number of watermain failures were associated with corrosion or corrosion

was an essential factor.

2. It is found that the break rate increases when the environment temperature (soil and water) is less than 0^0C. The total increase in pipe failures during winter, (35%), was twice and three times the total failures in summer and fall (12.9%, 16%) respectively.
3. The present analysis revealed that only a small number of pipes were responsible for the increasing number of pipe failures. Fifty percent of the pipes studied had experienced one break whereas only seven percent had experienced three breaks in a period of about twenty years.
4. From the developed models, it is concluded:
   - Two distinct types of main life stages were identified:

     - Up to the first break event where the pipe remains sound, it withstands different stresses and evaluates independently of time.

     -Beyond the first break event, the main break rate starts to increase exponentially.
   - The value for the growth rate coefficient, A_2, 0.4368 found in present study, is not comparable to the range of values for A_2 of 0.01 - 0.15 as found by Shamir and Howard [40] and 0.08 as measured by Clark [5]. The fact that the value of A_2 is higher than the upper end of the range indicates that the break rate increased rapidly with age, particularly during the time period 1968-1980. This suggests that the soils in the study area are corrosive to highly corrosive. A hypothesis that was verified by using corrosivity criteria classification of soils adopted after Baeckmann et al [2].
   - The variables in the existing Calgary data sets (soil resistivity and time from first break) were found to be useful in the description of the history of the calgary watermain de-

terioration:
- Soil Resistivity represents the level of corrosiveness of the soil. It appeared that the external corrosion played a great role in getting the pipe into the breaking stage. As the soil becomes corrosive (low resistivity), the pipe wall becomes more and more affected, weakened, and prone to breakage.
- Age from first break event was significant in predicting the total number of pipe failures over its lifetime. The pipe experiencing breaks early in its life would have much higher number of breaks than a pipe which experiences breaks later.

5. The present study suggests that the optimal replacement dates, based on economic criteria, can be used only as an indication of the degree of the pipe deterioration. Reliability criteria are difficult to quantify but significant in the timing of pipe replacement.

6. Throughout this study, difficulties were encountered in collecting and organizing the data. In many cases, the format for recording data was left up to various individuals and was, therefore, subject to individual discretion. Most of the data obtained from water utilities lacked consistency and completeness [5].

7.2 Recommendations for Further Research

Some work has been accomplished, but there are still several topics to be studied. The following topics for future research are proposed within the framework of the pipe failure analysis:

1. Water utilities need to institute careful record keeping procedures for tracking pipe repair and replacement costs. Significant savings can be achieved by replacing transmission mains at the

proper time. The issue of a system deterioration of water supply systems will no doubt become much more significant in the future.

2. This procedure can be extended to include the analysis of failure records of sewers and gas pipelines, depending on the availability of data. It may generate useful insights about the behavior of such transmission mains.
3. The proposed method can be extended also to include other factors such as water quality effects in unlined pipes, loss of carrying capacity and cleaning and lining processes.

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Appendix A

RECOMMENDATIONS FOR DATA COLLECTION AND ANALYSIS

A.1 Introduction

One major limitation in the application of the model proposed in this research is the lack of accurate and extensive historical records. The Calgary data set was not collected with the aim of doing an extensive analysis. Even if it possesses large amounts of data, it is rarely in a form easily accessible or useful in providing reliability analyses or developing decision-making criteria for repair or rehabilitation. However, even though the data are incomplete, this data set still represents one of the most comprehensive sources of information that is available. On the basis of this study of the Calgary water system, several recommendations can be made regarding the data collection and coding process for studies of this type.

A.2 Data Collection

Data collection or more appropriately data organization within most utilities is a painstaking process. The data are usually present in file cabinets, but they are of limited use in this form. The first step in developing a useful data base is to identify links and nodes for the system. A link should be defined as short segments, much shorter than what is typically used in the modeling of transmission mains. A link can be defined as a change in a diameter, an intersection or even a run of pipe between valves. Useful information for each link should include both nodes, pressure, installation date, diameter, material length, etc. Maintenance information should include the specific street address of maintenance event, type of problem (main line leak, joint leak), depth, type of action taken, location, environmental conditions, plus any other available information the utility desires.

In many cases the utility may keep fairly detailed and extensive maintenance records for purposes of cost accounting and scheduling of work crews. Even if these records are not in a form that is immediately convenient for statistical analysis, it might be worthwhile to record the data for this purpose. By recording available records for the last 20 to 40 years, the utility would obtain a data base that could be used to fit a model convenient to local conditions.

It may not be possible to reconstruct a data set from existing records. In this case, a utility could start out using known models (multivariate regression analysis [4], discriminant analysis [34] and other recent statistical models), choosing the one that seems more appropriate to the system in question as an aid to repair decisions. If it begins data collection within 15 to 20 years, it might have a large enough data base to formulate its own models based on local conditions, especially if there were a large number of breaks per year in the system. Managers of small systems or one with a low rate of pipe breaks might require a longer period of record collection before it could fit models.

A.3 Coding of Break-Type, Location and Repair Methods

It has been suggested, as shown in chapter 4, that the type of break is useful in determining a probable cause for the break. It is likely that many breaks are caused by external factors such as excavation by sewer contractors, etc. Further information on the time of the year, size or type of a break would be proven to be quite useful in the development of a water distribution system model. However, these limitations will be found in the historical records of most distribution systems.

Coding the exact locations of breaks and repair methods is not recommended to be very detailed because of the difficulty of coding and analyzing this kind of descriptive information (i.e., describing series of breaks closely spaced in time, and have been clustered together in location). However, it might be worthwhile to go back to the original records for a small sample of pipes that fit this pattern and see what caused the series of breaks.

A.4 Data Management

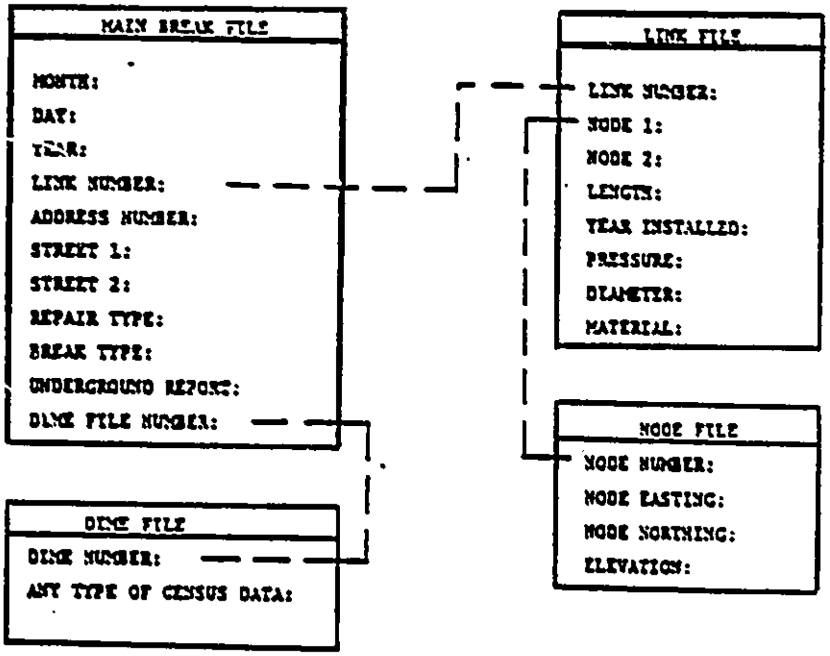
Data entry, storage, retrieval and file manipulation using spatial orientation on a microcomputer is best handled by a relational data base management system, DATABASE*III* PLUS for example. In this type of data base, data is organized into a series of interrelated two dimensional tables. Such a system is easy to reconstruct. Figure (A.1) is an example of a water distribution system network data can be organized in a relational form. Information from any table can be used in conjunction with retrievals through relationships shown by dotted lines. This form of data organization also allows expansion of the individual data base tables so that new types of information can be included with the existing types of data.

A very useful aspect of a relational data base management system is in its sorting capability. Sorting data by those mains with multiple maintenance events within a range of geographic references points can identify "hot spots" or pipes of similar characteristics that could then be taken as priority items for action.

In summary, in applying previous methods, these steps could be followed:

- Breaks could be marked on a network map to help identify simple geographic patterns.

Figure A.1: Example of Data Base Organization.



- Pipe links could be defined according to the criteria outlined above, and historical records of breaks coded along with available descriptive parameters for each pipe link such as length, diameter, installation date, pipe type and soil corrosivity along the pipe.

Appendix B

DATA OF THE CALGARY SOIL

Table B.1: Soil Corrosivity Index [2].

Index		
1.	Type of Soil	
	-limestone	
	-marl	+2
	-marl/sand	
	-sand	
	-clay, loam	
	-marl/clay	0
	-sandy clay	
	-sandy silt	
	-silt	
	-silt/marl	-2
	-humus	
	-peat	
	-mud	-4
	-bog soil	
2.	Soil Conditions	
	Water at structure level	
	-not present	0
	-present	-1
	-variable table	-1
	-natural soil	0
	-artificial soil	-2
	-soil uniform	0
	-soil nonuniform	-3
3.	Resistivity of Soil (ohm-cm)	
	> 10,000	0
	10,000-5,000	-1
	5,000-2,300	-2
	2,300-1000	-3
	< 1,000	-4
4.	Moisture Content	
	< 20%	0
	> 20%	-1

Index		
5.	pH	
	pH > 6	0
	pH < 6	-1
6.	Total Acidity	
	Total acidity to pH = 7	
	< 2.5 mval/Kg	0
	2.5 - 5.0 mval/Kg	-1
	> 5.0 mval/Kg	-2
7.	Redox Potential	
	parameter not measured.	
8.	Total Alkalinity	
	(As $CaCO_3$ content)	
	> 5% = 50,000 mg/Kg	+2
	1-5% = 10,000-50,000 mg/Kg	+1
	< 1% =10,000 mg/Kg	0
9.	H_2O and S^{--}	
	none	0
	< 0.5 mg/Kg S^{--}	-2
	> 0.5 mg/Kg S^{--}	-4
10.	Coal or Coke	
	none	0
	present	-4
11.	Chloride Ions	
	< 100 mg/Kg	0
	> 100 mg/Kg	-1
12.	Sulfate Ions	
	< 200 mg/Kg	0
	200-500 mg/Kg	-1
	500-1000 mg/Kg	-2
	> 1000 mg/Kg	-3

Table B.2: Chemical Composition and Other Physical Parameters of the Calgary Soil at Some Failure Sites

Soil Sample No.	Resistivity (ohm-cm)	pH**	Moisture Content (%)	Ion Concentration or Amount (mg/100 g of soil)												
				Cl^-	SO_4^{---}	HCO_3^-	S^{--}	Na^+	K^+	Ca^{++}	Mg^{++}	Acidity*	Alkalinity	Gravel	Sand	Clay Silt
1	1900	7.6	22.0	14.0	19.0	42	<0.1	4.5	1.2	8.0	6.0	<1	34	3	27	70
2	1600	8.2	18.1	15.0	10.0	107	<0.1	43.0	1.3	3.7	1.2	<1	83	3	31	66
4	1250	8.2	15.9	8.0	55.0	30	<0.1	9.0	2.3	16.0	8.0	<1	24	4	28	68
8	1400	7.7	17.8	4.0	38.0	44	<0.1	10.5	1.5	11.0	8.5	<1	36	0	15	85
9	1900	7.8	16.3	3.0	12.0	51	<0.1	19.0	1.2	3.9	3.1	<1	42	0	7	93
11	3200	8.2	16.7	2.5	4.0	49	<0.1	4.6	1.2	4.2	7.4	<1	40	0	16	84
13	820	8.3	20.7	11.0	118.0	43	<0.1	16.0	2.0	42.0	12.0	<1	35	8	21	71
14	4300	8.1	26.5	<1.0	2.0	43	<0.1	3.6	1.1	6.6	3.4	<1	35	1	7	92
15	3700	8.1	21.1	1.0	6.0	44	<0.1	7.4	1.5	5.0	4.1	<1	36	2	15	83
17	2800	8.0	25.2	7.5	7.5	43	<0.1	4.1	5.0	7.0	5.9	<1	35	0	40	60

* As $CaCO_3$

** $1:5 Aqua$

Appendix C

ECONOMIC ANALYSIS

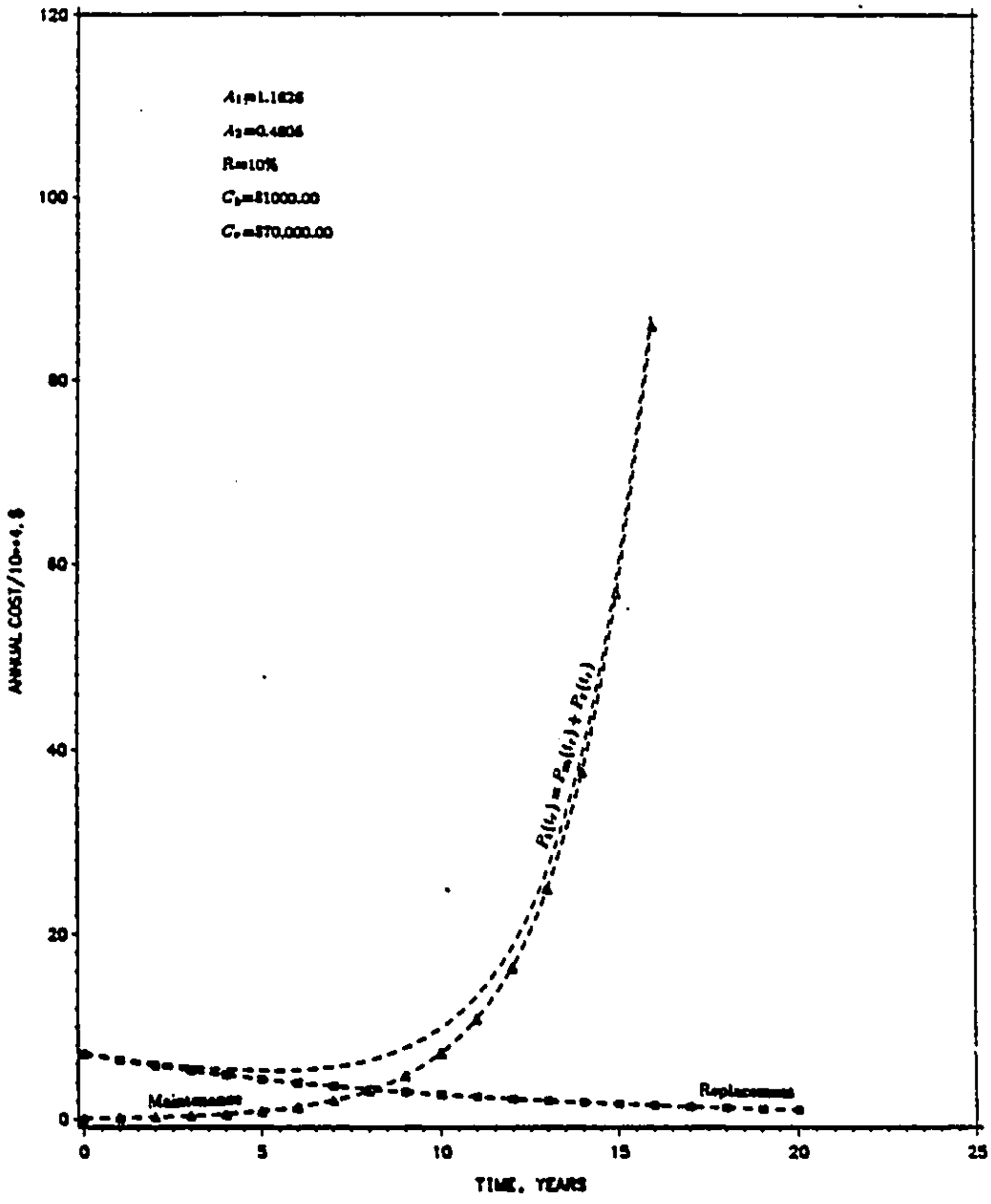


Figure C.1: Future Maintenance and Replacement Costs.(1).

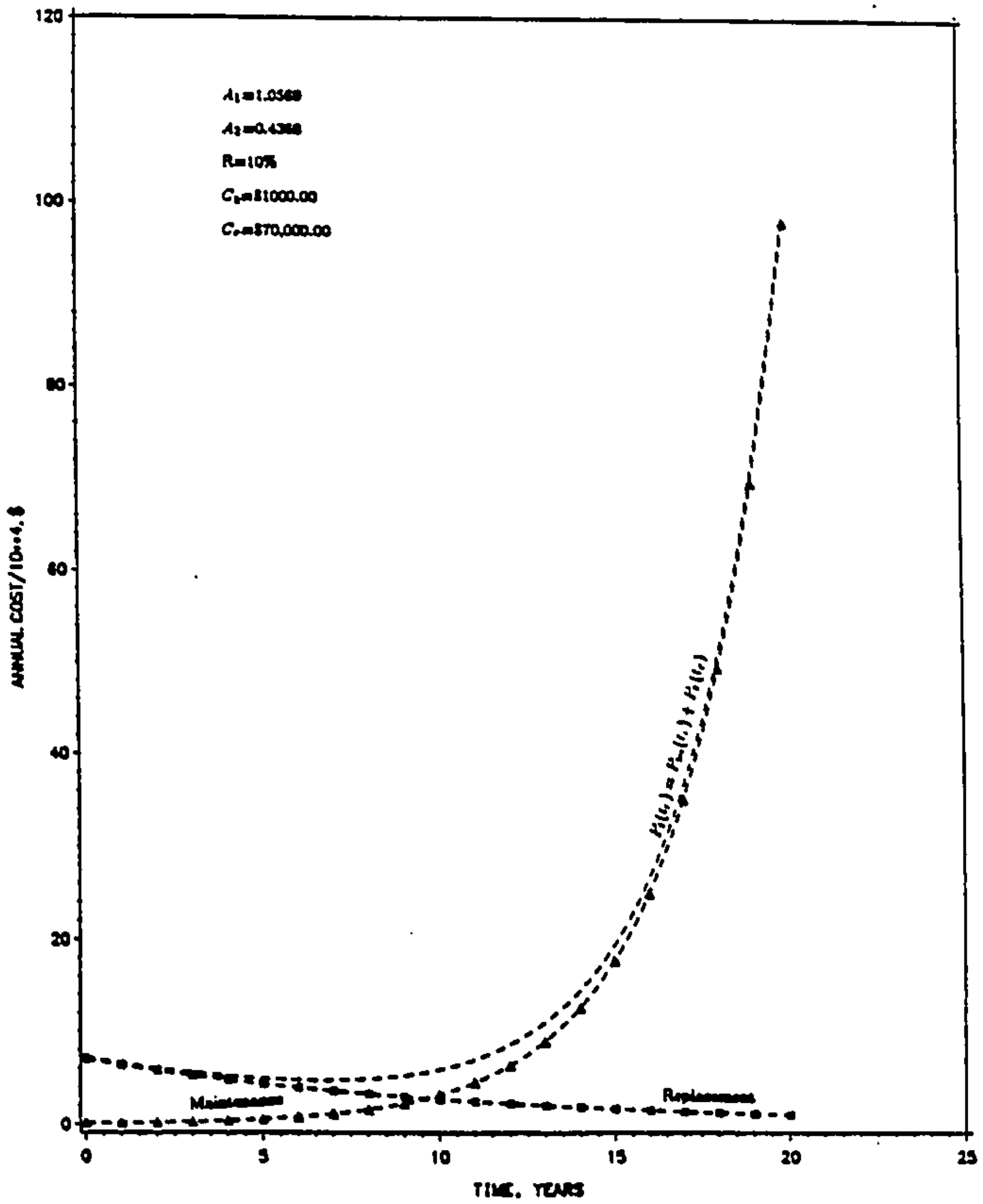


Figure C.2: Future Maintenance and Replacement Costs (2).

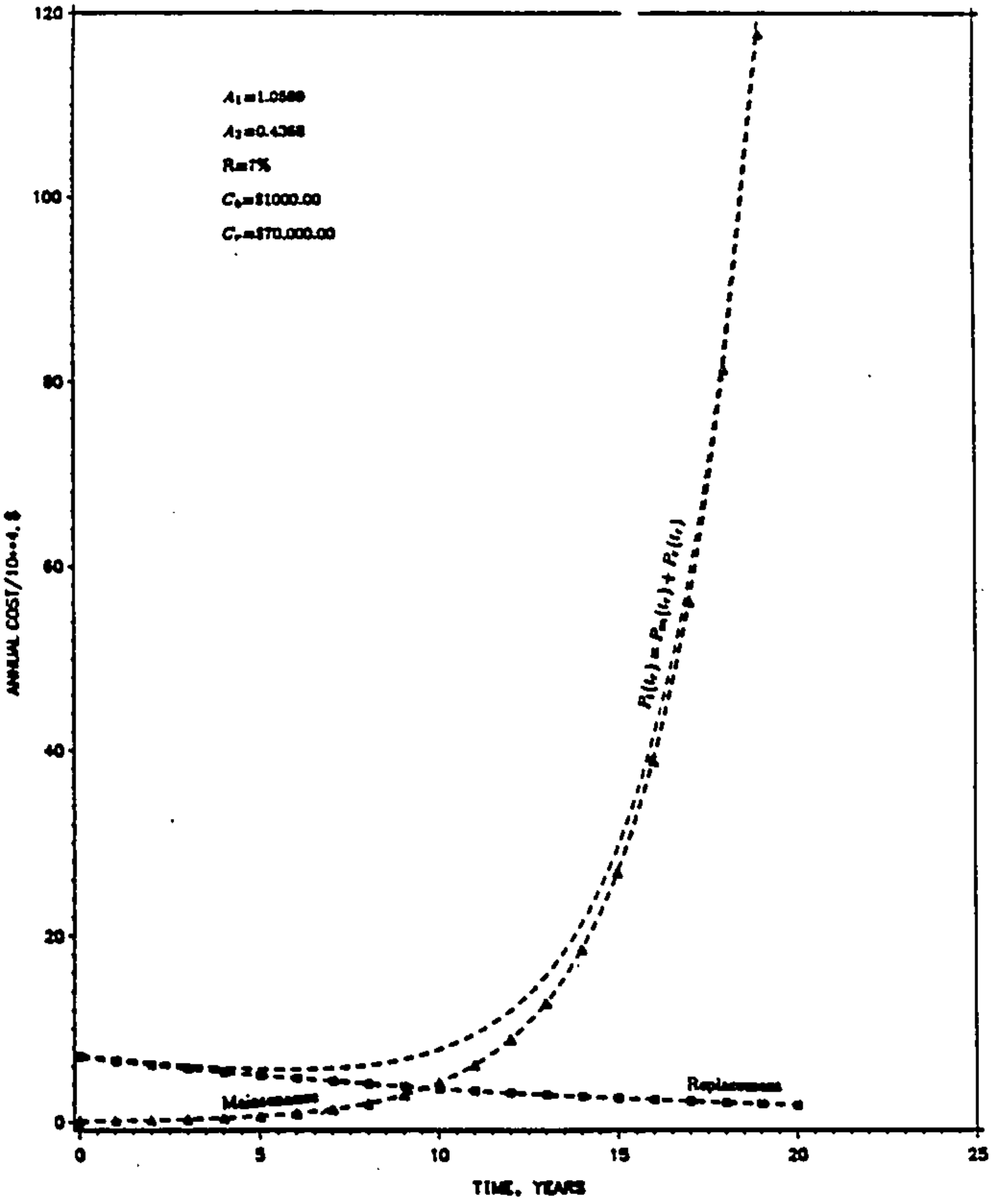


Figure C.3: <u>Future Maintenance and Replacement Costs</u> (3).

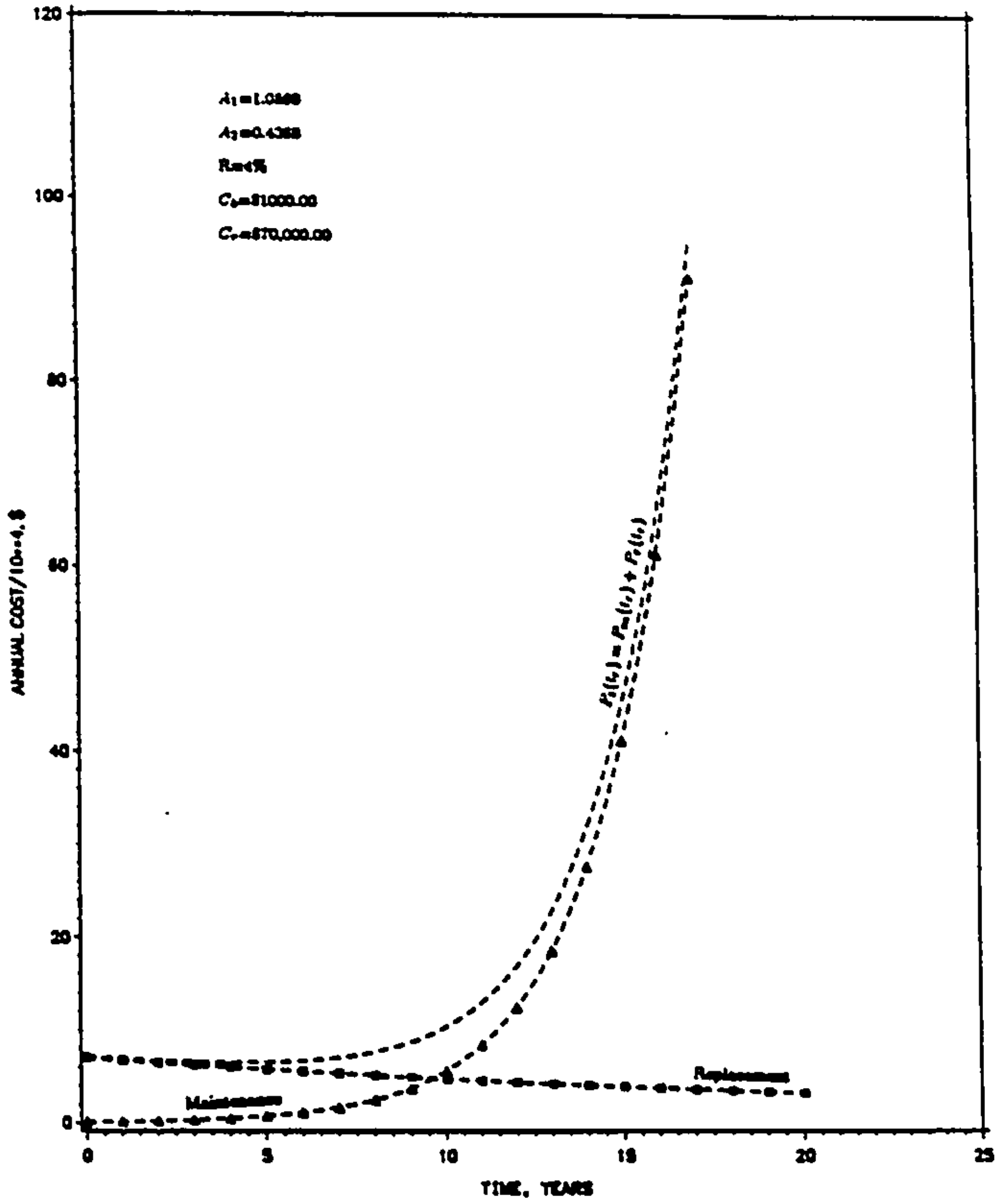


Figure C.4: <u>Future Maintenance and Replacement Costs</u> (4).

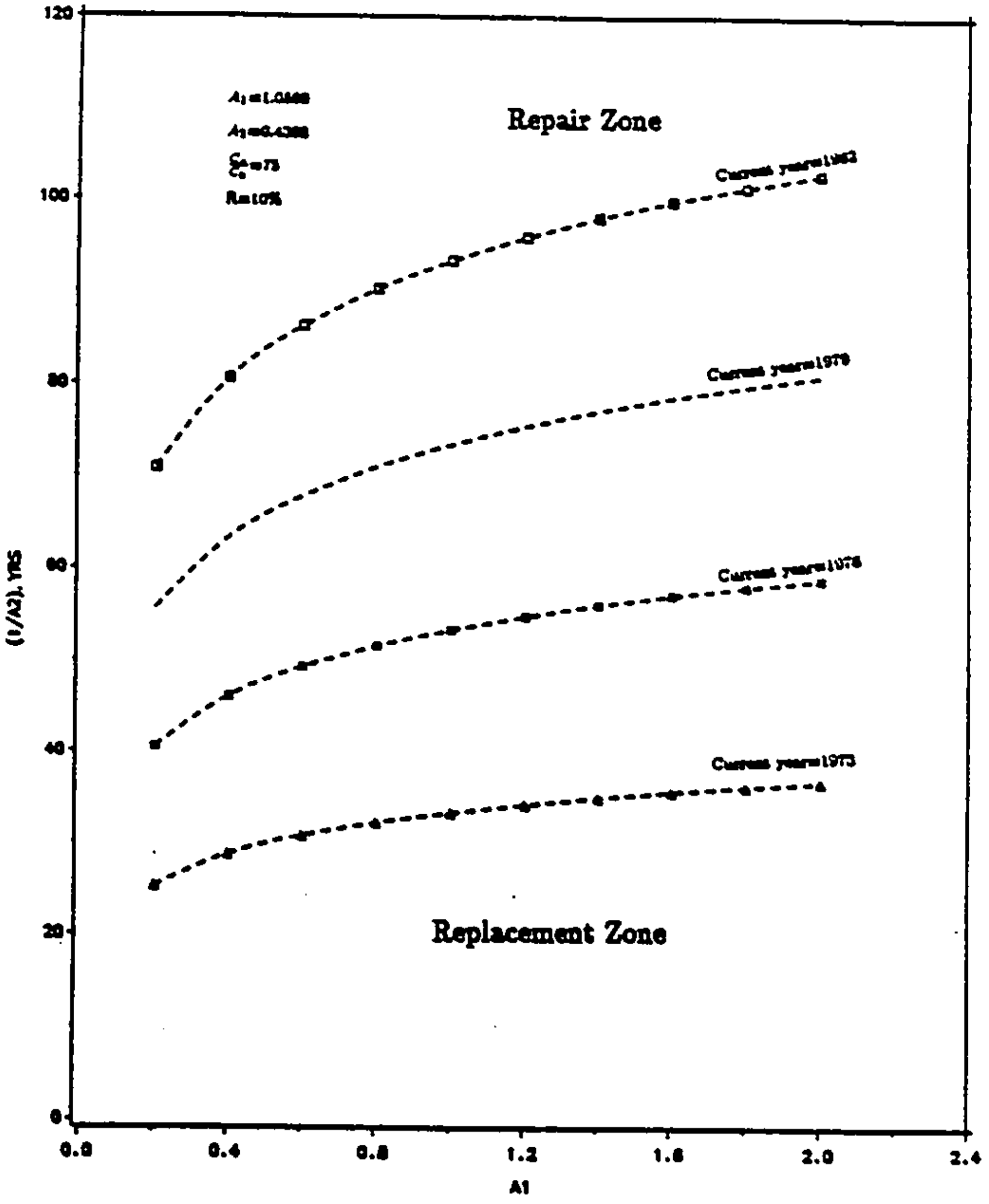


Figure C.5: <u>Optimal Pipe Replacement Dates</u> (1).

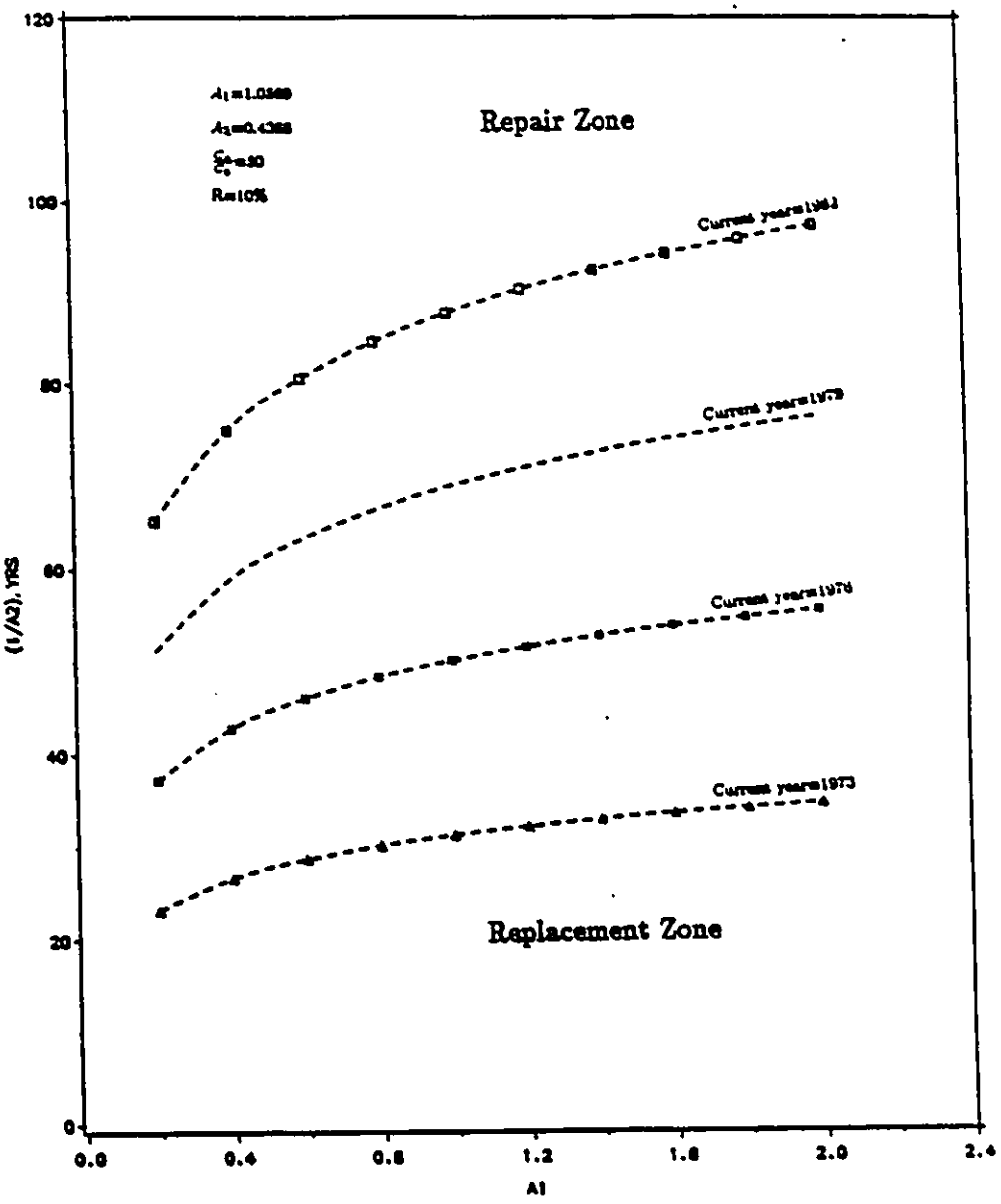


Figure C.6: Optimal Pipe Replacement Dates (2).

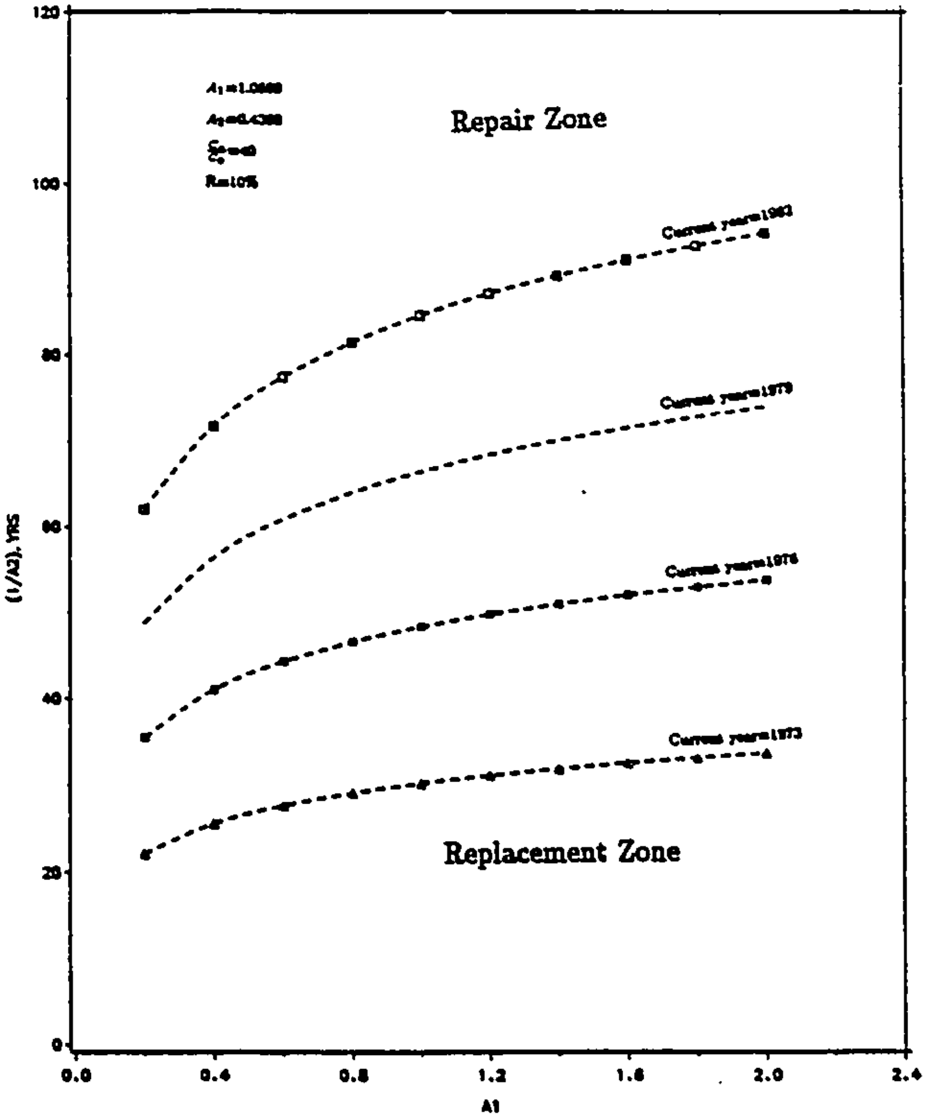


Figure C.7: Optimal Pipe Replacement Dates (3).

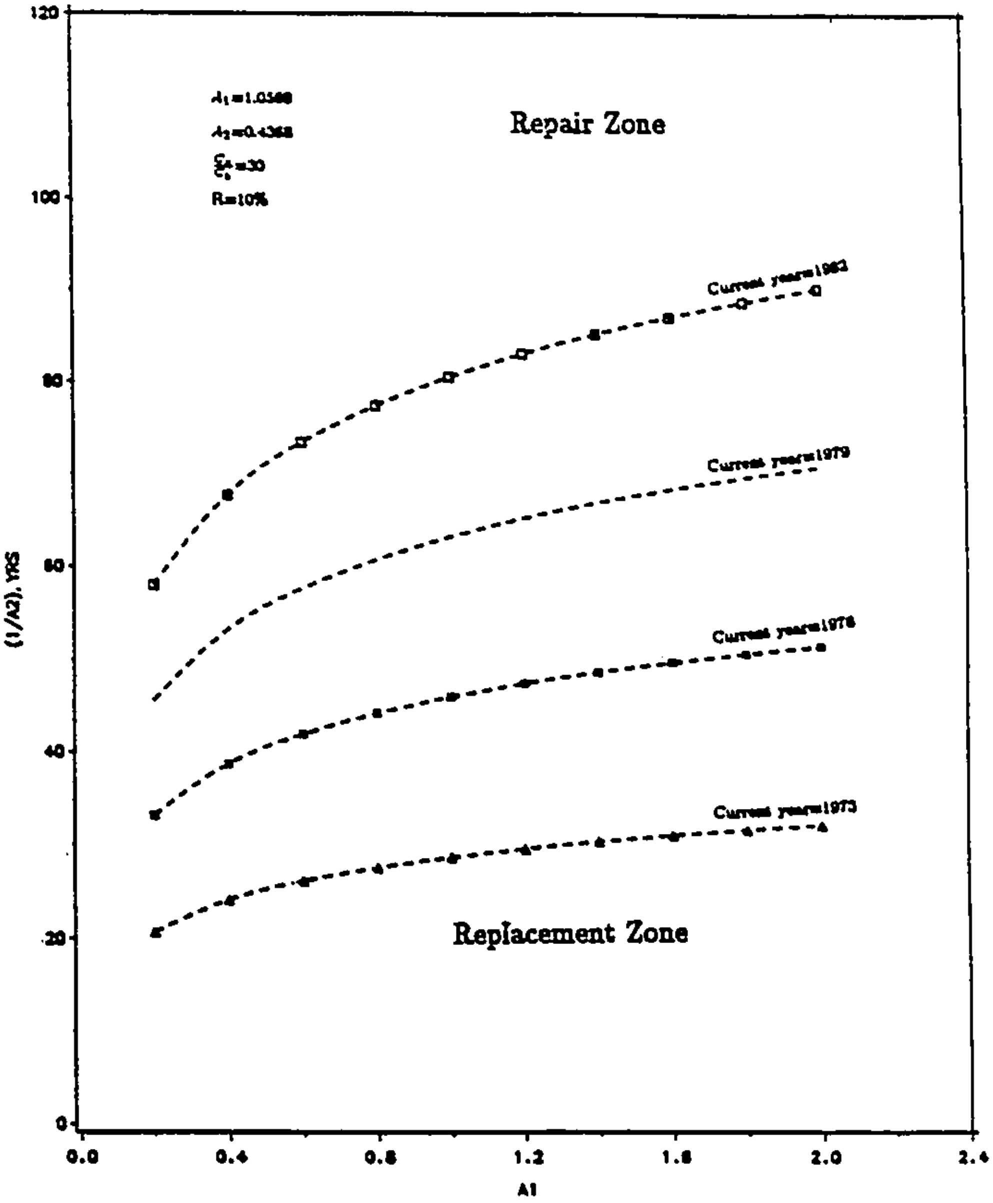


Figure C.8: <u>Optimal Pipe Replacement Dates</u> (4).

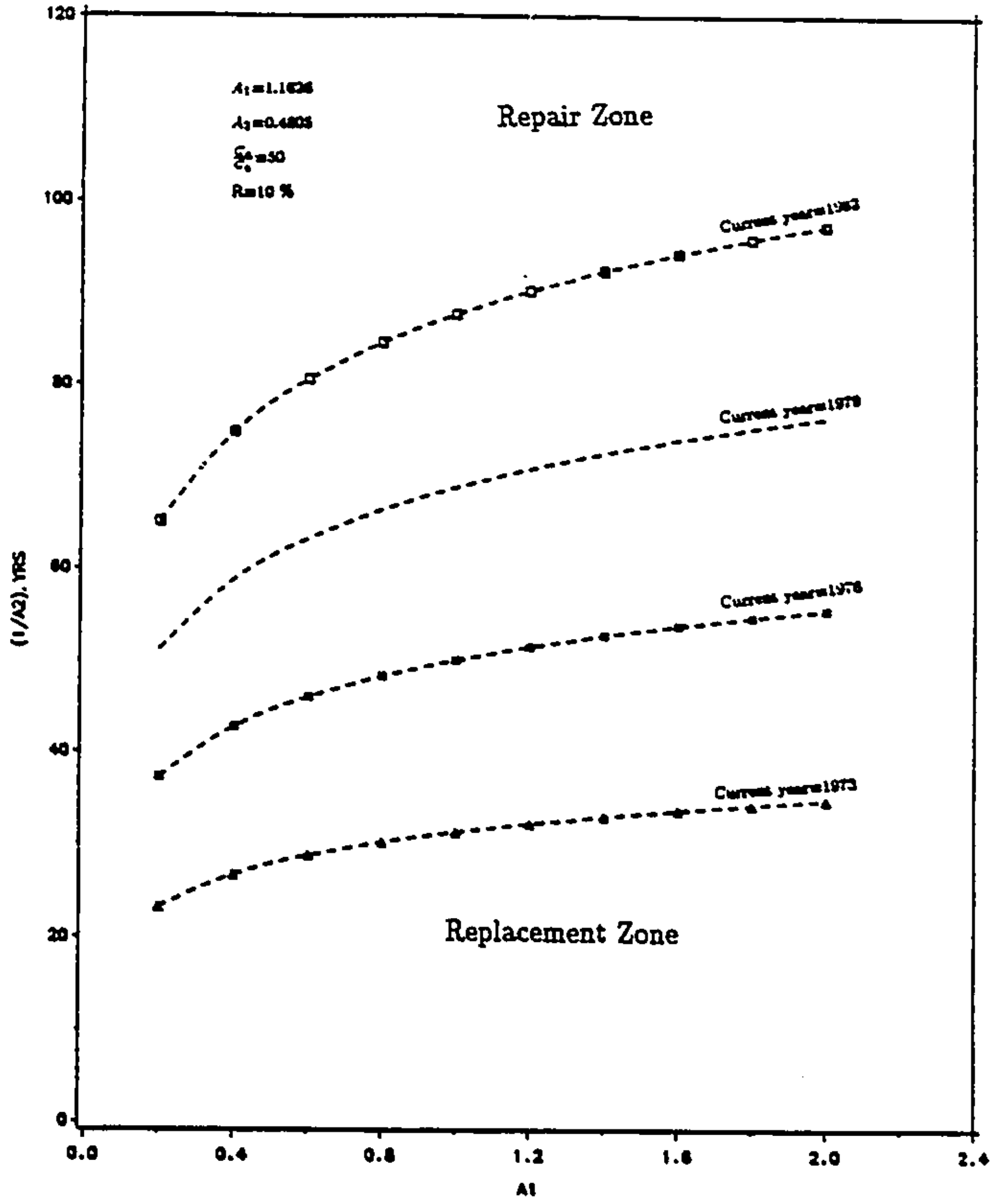


Figure C.9: <u>Optimal Pipe Replacement Dates</u> (5).

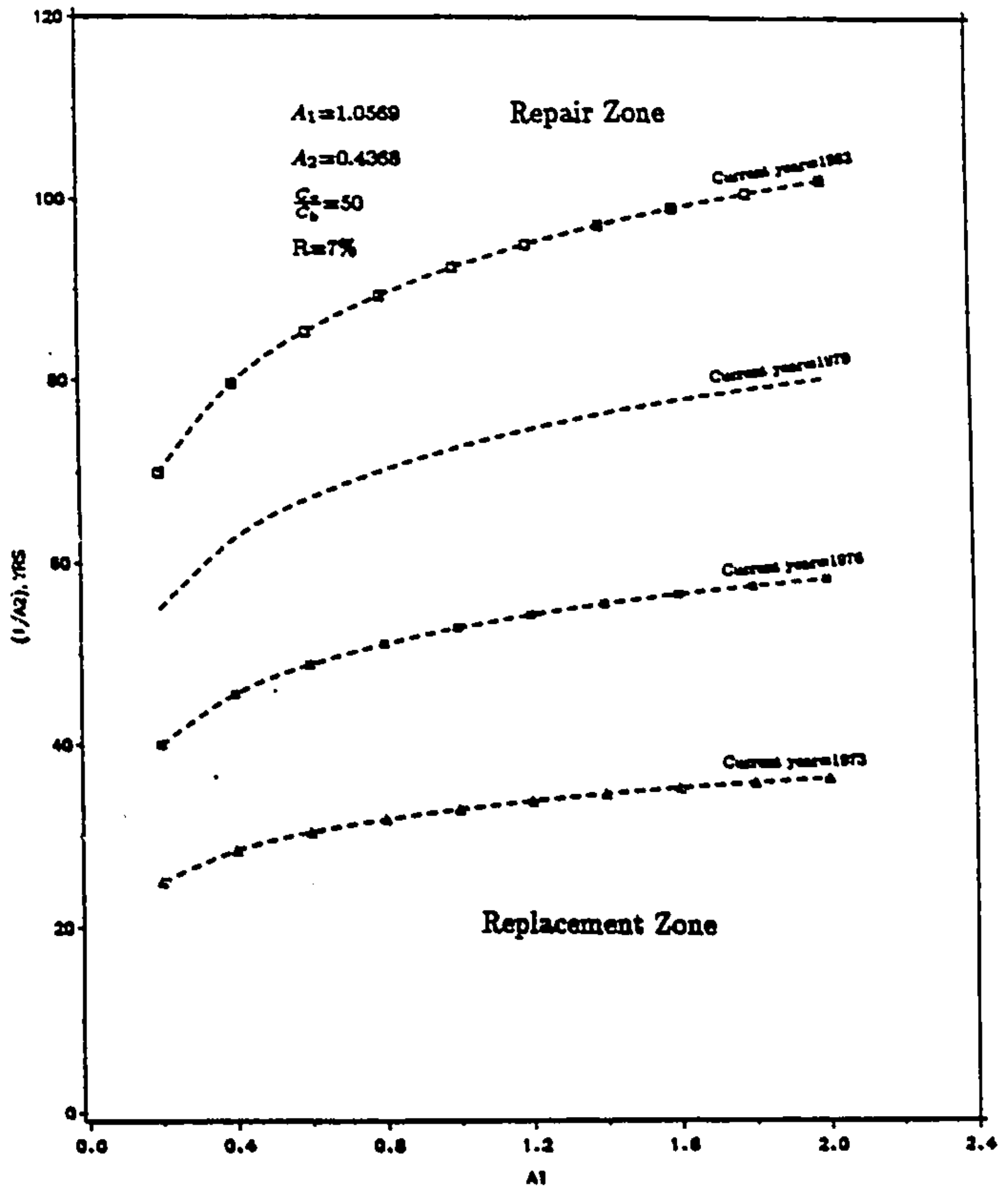


Figure C.10: Optimal Pipe Replacement Dates (6).

Appendix D

SAMPLE SAS PROGRAMS

```
OPTIONS NODATE CENTER ;

TITLE 'TABLE(..) PREDICTION OF TIME TO FIRST FAILURE OF WATER PIPES';

DATA C;
     INPUT X1 X2 X3 Y1 ;
     LABEL Y1='TIME TO THE FIRST PIPE FAILURE, YRS.'
     LABEL X1='SOIL RESISTIVITY, OHM.CM.'
     LABEL X2='SOIL PH.'
     LABEL X3='PIPE WALL THICKNESS, MM.' ;
CARDS;
        4300 8.10000 11.1000 30.0000
        3700 8.10000 10.7000 25.0000
        3200 8.20000 11.6500 16.0000
        2800 8.00000 11.9000 22.0000
        1900 8.10000 10.0000 15.0000
        1900 7.80000 10.4000 15.0000
        1850 7.80000 13.3000 15.0000
        1600 7.90000  8.0000  9.0000
         600 8.00000  9.8000 13.0000
        1450 7.80000  8.6000 12.0000
        1450 7.70000  7.6000 10.0000
        1400 7.70000  6.6000 11.0000
        1250 8.00000  6.7500 10.0000
        1200 7.10000  7.0000 10.0000
         820 7.30000  6.8000 17.0000
         580 7.50000  7.5000  5.0000
;
PROC SORT DATA=C;
    BY DESCENDING  Y1      ;
PROC PRINT U;
PROC CORR;
    VAR Y1 X1 X2 X3     ;
PROC STEPWISE ;
    MODEL Y1 = X1 X2 X3      ;
/* PROC REG DATA=C ;              */
    VAR X1 X2 X3  Y1     ;
    MODEL Y1 =  X1 X2 X3    ;
/* OUTPUT OUT=C P=PRED L95=L95 U95=U95 R=RESID ;   */
PROC PLOT DATA=C;
/* PLOT Y1*X1 ='#'  / OVERLAY VPOS=32 HPUS=80;       */
/* PLOT RESID*X1 ='#'  / OVERLAY VPOS=32 HPOS=80;    */
/* PLOT RESID*PRED='+'  / OVERLAY VPOS=32 HPOS=80;   */
/* PLOT X1*X3 ='+'  / OVERLAY VPOS=32 HPOS=80;       */
RUN ;
```

Figure D.1: Prediction of Time to First Pipe Failure.

```
OPTIONS NONUMBER NODATE CENTER;
TITLE1 'TABLE(..) PREDICTION OF BREAK RATE OF WATER PIPES';

DATA C;
     INPUT Y1 X1 X2 X3    ;
     LABEL Y1='ANNUAL BREAK RATE, BREAK PER YR. PER LENGTH.'
     LABEL X1='EXP(TIME FROM FIRST BREAK EVENT, YRS).'
     LABEL X2='EXP(PIPE LENGTH, KM).'
     LABEL X3='EXP(PERCENT OF PIPE IN DEVELOPED AREA, %).';
CARDS;
   1.00  0   30.5 12.
   4.00  1   86.8 25.
   5.00  2  147.1 13.
   9.00  3  100.9 15.5
  38.00  4  201.3 35.45
  45.00  5  218.5 26.66
  58.00  6  306.4 19.83
  95.00  7  402.1 29.44
  89.00  8  574.6 62.45
 168.00  9  671.4 13.89
 198.00 10  677.6 68.01
 369.00 11  754.3 70.2
 398.00 12  858.0 84.92
 500.00 13  744.6 39.8
  ;
PROC PRINT DATA=C;
/*   BY DESCENDING  Y1 ;              */
PROC CORR                       ;
/*   VAR Y1 X1 X2 X3    ;              */
PROC STEPWISE                   ;
      MODEL  Y1= X1 X2 X3         ;
/* PROC REG DATA=C                    ;        */
    VAR Y1 X1 X2 X3             ;
    MODEL  Y1= X1 X2 X3         ;
/* OUTPUT OUT=C P=PRED L95=L95 U95=U95 R=RESID STDR ;    */
PROC PLOT DATA=C;
    PLOT Y1*X1='+' Y4*X1='#'/ OVERLAY VPOS=32 HPOS=80;
/* PLOT X1*X2='*' / VREF=0 VPOS=18 HPOS=80;                */
/* PLOT X1*X3='#'  / OVERLAY VPOS=32 HPOS=80;              */
/* PLOT X1*X2='#'  / OVERLAY VPOS=32 HPOS=80;              */
/* PLOT RESID*X1='+'  / OVERLAY VPOS=32 HPOS=80;           */
/* PLOT RESID*PRED='+'  / OVERLAY VPOS=32 HPOS=80;         */
RUN;
```

Figure D.2: Prediction of Break Rate of in Water Pipes.