PROBABILITY OF FAILURE ANALYSIS AND CONDITION ASSESSMENT OF CAST IRON PIPES DUE TO INTERNAL AND EXTERNAL CORROSION IN WATER DISTRIBUTION SYSTEMS

by

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ABSTRACT

Corrosion of cast iron pipes in distribution systems can lead to the development of corrosion pits that may reduce the resistance capacity of the pipe segment, resulting in mechanical failure. These pipes have a tendency to corrode externally and internally under aggressive environmental conditions. The mechanical failure of pipes is mostly the result of this structural weakening coupled with externally, environmental, and internally, operational, imposed stresses. While external corrosion has been shown to significantly affect the likelihood of mechanical failure, the risk of failure may be further heightened if internal corrosion is occurring.

This thesis develops a methodology for estimating the probability of mechanical failure of cast iron pipes due to internal corrosion that incorporates the relationship between chlorine consumption and the rate of internal corrosion in a cast iron pipe. A probability analysis is developed that incorporates the internal corrosion model as well as the Two-phase nonlinear external corrosion model to calculate the overall probability of mechanical failure. Monte Carlo Simulation (MCS), First Order Reliability Method (FORM)-, and Second Order Reliability Method (SORM)-based approaches are used to estimate the probability of mechanical failure.

Next, a methodology is developed for analyzing pipe condition based on the data resulting from the probability of mechanical failure analysis incorporating internal and external corrosion. A modeling strategy inspired by survival analysis is used to obtain the predicted number of pipe breaks for a given exposure time. The likelihood of failure at a given residual pipe wall thickness is estimated and coupled with the predicted number of pipe breaks as surrogates for pipe condition. These condition indices may support decisions regarding replacement planning and can be coupled with economic assessment models in the development of future asset management strategies.

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A = pipe effective length on which load is estimated (mm);

a = final pitting rate constant (0.009 mm/yr);

a_1 = constant used to determine pipe strength capacity;

a_n = lateral dimension of pit depth (mm);

b = pitting depth scaling constant (6.27 mm);

b_1 = constant used to determine pipe strength capacity;

B_d = width of the ditch (mm);

C_0 = the initial chlorine concentration at time t = 0 (mg/l);

C_d = calculation coefficient for soil pressure which needs to be selected for a given situation on the basis of imperfect information (typically between 1.12 and 1.52);

Cl_2 = chlorine concentration (mg/l);

C_r = internal corrosion rate (µm/year);

$C_{r(int)}$ = internal corrosion rate (µm/year);

$C_{r(ext)}$ = external corrosion rate (µm/year);

C_t = chlorine concentration at any time t (mg/l);

C_s = surface load coefficient that describes the distribution of traffic loads and needs to be selected for a given situation (typically between 0.96 and 0.144);

$\frac{C_t}{C_0}$ = chlorine concentration ratio;

c = corrosion rate inhibition factor (0.14/yr);

D = pipe diameter (m);

d^* = corrosion pit depth (mm);

d^*_{ext} = external corrosion pit depth (mm);

d^*_{int} = internal corrosion depth (mm);

d_p = maximum acceptable decrease in pipe wall thickness;

E_p = modulus elasticity of the pipe (Mpa);

F = wheel load of traffic (N);

$F(T)$ = cumulative probability function of pipe failure;

$F(T_{1,2})$ = cumulative probability function of pipe failure at times T_1 and T_2;

$f(T)$ = probability distribution function of pipe failure;

$f_1(T)$ = probability distribution function of pipe failure associated with Weibull distribution;

f_{frost} = frost load multiplier;

I_c = impact factor coefficient that determines the impact of surface loads on a pipe segment for a given situation (typically between 1.125 and 1.875);

K = chlorine decay constant (mg/l);

K_a = constant used in empirical power model (typically=2);

K_d = deflection coefficient that depends on the distribution of the vertical loads on the top of the pipe and associated reaction on the bottom of the pipe for a given situation (typically between 0.0864 and 0.1296);

K_m = bending moment coefficient that depends on the distribution of vertical load on the top of the pipe and associated reaction on the bottom of the pipe for a given situation (typically between 0.185 and 0.285);

K_n = constant;

K_q = measurable fracture toughness (constant value for cast iron pipe=10) (MPa $m^{1/2}$);

k = parameter of Weibull distribution;

k_2 = parameter of Exponential distribution;

L = pipe length (m);

n_a = constant used in empirical power model (typically=0.3);

n = soil redox potential (related to soil oxidation);

p = parameters of Weibull distribution;

p_i = internal fluid pressure (MPa);

pH = soil acidic and alkaline nature;

$S(T)$ = survival function associated with the Weibull distribution at time T;

$S(T_{1,2})$ = survival functions associated with the Weibull distribution at times T_1 and T_2;

T = exposure time (year);

t = time of travel within the pipe over its entire length under a given design flow regime (s);

t_p = original pipe wall thickness (mm);

t_{res} = residual pipe wall thickness (mm);

t_{res} = residual thickness (mm);

V = water velocity (m/s);

σ_θ = total circumferential stress (MPa);

σ_F = stress due to internal fluid pressure (MPa);

σ_S = stress due to soil pressure (MPa);

σ_L = stress due to frost pressure (MPa);

σ_V = stress due to traffic loads (MPa);

σ_X = total longitudinal stress (MPa);

σ_Y = pipe strength capacity (MPa);

σ'_F = stress due to internal pressure in longitudinal direction (MPa);

σ_T = stress related to temperature differences along the pipe (MPa);

γ = unit weight of the soil (N/mm^3);

$\lambda(T)$ = hazard function (failure rate);

ρ_{soil} = soil resistivity;

υ_p = pipe material Poisson ratio;

α_p = constant thermal expansion coefficient of pipe (typically 11×10^{-6});

β = geometric factor;

ΔT = temperature differential (^{0}C);

α, S = constants used in fracture toughness equations.

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CO-AUTHORSHIP STATEMENT

Hamidreza Yaminighaeshi was the lead and principal researcher of the work contained in the thesis titled "Probability of failure analysis and condition assessment of cast iron pipes due to internal and external corrosion in water distribution systems". Dr. Barbara Lence, the Research Supervisor of the thesis, provided inspiration and supported the writing of the papers included in thesis.

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION, THESIS QUESTIONS, AND OBJECTIVES

Our understanding of the failure behavior of a pipe segment can be improved by predicting the likelihood of failure of a water main for a given exposure time. Analyzing the probability of failure in pipes can serve the following important purposes. It can be used to: 1) determine the contribution of internal corrosion to the overall probability of mechanical failure, 2) determine the parameters that have the most significant effect on the overall probability of failure, and 3) identify pipe condition indices to assist in the long-term planning of the renewal of water distribution systems. This information may, in turn, be used to perform economic evaluation to determine an optimum replacement time for water mains that are failing due to corrosion and the budgetary needs for future repairs under various replacement and rehabilitation strategies as part of a comprehensive asset management analysis.

The research questions that will be addressed in this thesis are:

1. How may the probability of mechanical failure due to internal corrosion during the exposure time be determined?
2. What corrosion parameters significantly affect the failure probability due to internal corrosion?
3. How may uncertainties in corrosion parameters be accounted for when analyzing mechanical pipe failures due to internal corrosion?
4. How may the probability of mechanical failure due to internal and external corrosion during the exposure time be determined?
5. How may one estimate the predicted annual number of failures of cast iron pipes due to internal and external corrosion?
6. How may one use the probabilistic analysis for assisting in condition assessment and long-term planning for replacement of water mains in a distribution system?

These questions are designed to increase our understanding of failure behavior of cast iron pipes and the condition of assets, e.g., water mains, to assist in developing future planning strategies. The high degree of uncertainty associated with parameters that affect pipe failures warrants a probabilistic-based analytical approach. A detailed uncertainty analysis is required to quantify the probability of pipe failures at a given time and to plan maintenance, replacement, and repair strategies.

This research develops a probability analysis of mechanical failure due to internal and external corrosion and identifies pipe condition indices to assist in the long-term planning of the renewal of water distribution systems. The objectives of the research are:

- *To develop a methodology for estimating the probability of mechanical failure of cast iron pipes due to internal corrosion.*

A probabilistic analysis is developed that identifies and incorporates the relationships between water quality parameters, e.g., the chlorine concentration ratio, hydraulic performance, e.g., the velocity, and the rate of internal corrosion. Monte Carlo Simulation (MCS), First Order Reliability Method (FORM)-, and Second Order Reliability Method (SORM)-based approaches are used for estimating the probability of mechanical failure due to internal corrosion. The corrosion depth is estimated based on the assumption that the rate of corrosion is constant throughout the exposure time, at least after the pipe is 18 months old (Snoeyink and Wagner 1996). Mechanical failure is defined as the point at which the corrosion depth is more than the maximum acceptable decrease in pipe wall thickness set by the utility manager. The probability of failure for a given exposure time is determined and may be thought of as a surrogate for the service life of a pipe. A sensitivity analysis is conducted to determine the sensitivity of the estimates of the failure probability to each of the uncertain inputs of internal corrosion.

- *To estimate the probability of mechanical failure of cast iron pipes due to both internal and external corrosion.*

A probabilistic analysis is used that incorporates the Two-phase external corrosion model as well as the internal corrosion model developed in the first objective to calculate the probability of pipe failure. The failure definitions based on the difference between the stresses acting on a pipe segment and the pipe strength capacity may be compared with the failure definition for the probability of failure due to the external corrosion estimated by Rajani et al. (2000). A sensitivity analysis is conducted to determine the sensitivity of the estimates of the failure probability to each of the uncertain inputs of both internal and external corrosion.

- *To develop an approach for assisting in predicting condition of water mains over time using the probability of failure due to corrosion and a modeling strategy inspired by survival analysis.*

This approach uses the probability of failure due to internal and external corrosion and incorporates a modeling strategy to obtain the condition of water mains. A modeling strategy, inspired by survival analysis, is employed to predict the structural behavior of a pipe over time. Survival analysis, which describes the likelihood of a pipe surviving at a given exposure time, is a statistical technique that draws upon the outputs of probability of failure analyses to predict the annual number of pipe breaks over time.

Probability density, hazard, and survival functions are estimated based on the results of probability analyses due to internal and external corrosion. The estimated survival function developed in this work compares well with other survival functions based on case studies developed by Pelletier et al. (2003). The estimated probability density, hazard, and survival functions are then used to estimate the number of pipe breaks that may be expected throughout the exposure time.

The annual number of pipe failures for a given pipe segment may be considered as a first indicator of pipe condition in water distribution systems. The likelihood of failure for a given residual pipe wall thickness, e.g., as a second indicator of pipe condition, and the number of predicted breaks may be used to support decisions regarding pipe replacement and can be coupled with economic assessment models to develop future asset management strategies.

This Chapter reviews the corrosion phenomena in cast iron pipes, including problems associated with corrosion, corrosion rates, pipe failure mechanisms, and factors affecting internal and external corrosion. It describes the current models for predicting corrosion pit depths and for estimating loads acting on cast iron pipes, the existing probabilistic models for estimating the probability of failure at a given exposure time, and condition assessment and approaches for long-term replacement planning of cast iron pipes. The structure of the thesis is also described herein.

1.2 BACKGROUND

1.2.1 Electrochemical Corrosion

Pipe material deterioration is due to the internal and external chemical, biochemical, and electrochemical environment. The most effective deterioration mechanism of the exterior of cast iron pipes is electrochemical corrosion (Rajani and Kleiner 2001). Also, Benjamin et al. (1996) report that the deterioration of the interior surface of such pipes due to corrosion is governed by electrochemical reactions. This type of corrosion damages the pipe surface and creates corrosion pits.

Electrochemical corrosion is the destruction of a metal by electron transfer reactions. For this type of corrosion to occur, all components of an electrochemical cell must be present. These components include an anode and a cathode, which are sites on the metal that have different electrical potential; a connection between the anode and cathode for transporting electrons, i.e., an internal circuit; and an electrolyte solution that will conduct ions between the anode and cathode, i.e., an external circuit. The oxidation of metal occurs at the anode. In the case of internal corrosion, the electrons generated by the anodic reaction transport through the internal circuit, i.e., the pipe surface, to the cathode, where they are discharged to a suitable electron acceptor such as oxygen or chlorine, by a chemical reduction reaction. The positive ions generated at the anode will tend to be transported through solution, i.e., the bulk water, to the cathode, and the negative ions generated at the cathode will tend to be transported to the anode. The distribution of anodic and cathodic areas over the corroding material is defined as electrochemical corrosion. Figure 1.1 shows a schematic of an internal corrosion cell in a pipe segment.

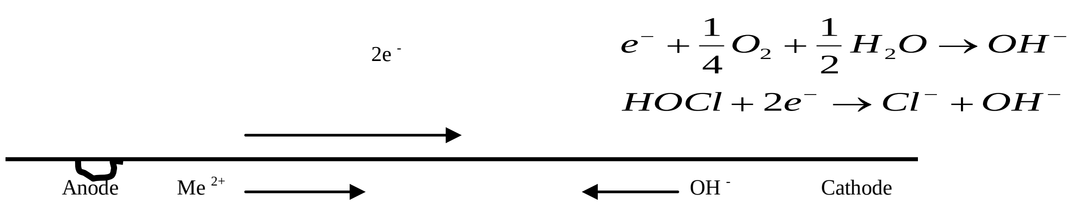

Figure 1.1. Schematic of a corrosion cell (Adapted from Snoeyink and Wagner, 1996)

1.2.2 Corrosion problems

Two types of electrochemical corrosion considered in this research are external and internal corrosion. External corrosion of pipes in distribution systems can lead to the development of corrosion pits that may reduce the resistance capacity of the pipe segment, resulting in mechanical failure. Internal corrosion may lead to two major problems. The first problem is water leakage and loss of hydraulic capacity caused by the loss of pipe wall thickness and build up of corrosion products, i.e., scale layers. The second problem is the change in water quality as water travels through corroding pipes in the distribution system. This impact is caused by corrosion products entering the water, causing, for example, red water, and reducing the chlorine residual. In this research, the mechanical failure of water mains due to external and internal corrosion is considered and the second type of failure, i.e., the water quality problem, due to internal corrosion will be reserved for future research.

1.2.3 Corrosion rates

The loss of pipe wall thickness due to the corrosion process can be either uniform around the pipe or localized. The corrosion phenomenon is complex, and the rate of wall loss due to both internal and external corrosion, as well as whether the rate is constant or variable, has been the subject of debate (Melchers 1996 and Snoeyink and Wagner 1996).

Corrosion may be considered as a self-inhibiting process whereby the protective properties of corrosion products reduce the corrosion rate over time and then stabilize the rate at a specific value thereafter. The most common external and internal corrosion models will be reviewed in Section 1.2.6 of this chapter. These models relate the corrosion depth with the pipe age and may be used to predict the remaining service life of water mains.

1.2.4 Pipe failure mechanisms

The physical mechanisms that lead to pipe breakage involve three principal aspects: 1) internal loads due to operational fluid pressure and the external loads due to soil pressure, frost pressure, traffic loads, stress due to temperature differences along the pipe and third parties, 2) material deterioration due to internal and external corrosion, and 3) failure due to pipe structural properties, type of material, pipe-soil interaction, and quality of pipe installation.

Pipe failure is likely to occur when the total pressure, including internal water pressure, soil pressure, frost pressure, traffic loads, and pressure gradients due to temperature differences along the pipe act on pipes in which structural integrity has been reduced by corrosion or inadequate installation. These parameters contribute to reducing the life of the pipe and result in mechanical failure. In this research, the effect of external and internal loads and external and internal corrosion will be modeled to determine the probability of mechanical pipe failure.

Bending stress due to soil movement and pipe installation quality has not been modeled due to the varied, uncertain, and complex parameters involved in installation and in modeling the installation process.

1.2.5 Parameters affecting internal and external corrosion

Several parameters affect external corrosion including the soil acidity, alkalinity, and temperature. Similarly, a number of parameters affect pipe internal corrosion including the water quality, i.e., pH, alkalinity, concentration of disinfectants, and flow conditions, i.e., water velocity.

There is a high degree of uncertainty associated with all of the parameters contributing to pipe mechanical failure, and especially with corrosion rates because of the large spatial and temporal variability of these parameters. The uncertainty related to many of these parameters is addressed in this study through the use of probability and sensitivity analyses.

1.2.6 Modeling of corrosion

This section reviews existing external and internal corrosion models which are used in this study to determine the probability of mechanical failure of cast iron pipes in water distribution systems.

1.2.6.1 External corrosion models

Four empirically-based external corrosion models are used in practice. They are the Two-phase, linear, and two types of power models.

Rajani et al. (2000) develop the Two-phase empirical corrosion model which is based on the assumption that the corrosion rate is generally high during early pipe ages and then stabilizes at a certain value thereafter. In the first phase of the Two-phase model, a rapid exponential pit growth occurs and in the second phase a slow linear pit growth occurs due to the corrosion self-inhibiting process. This model is defined as:

$$d^* = aT + b(1 - e^{-cT}) \qquad (1.1)$$

The empirical linear model is developed by Sheikh et al. (1990) for the determination of corrosion pit depth as a function of pipe age. Here, the value of the corrosion rate is considered constant over time. The model is defined as:

$$d^* = C_{r(ext)} \times T \qquad (1.2)$$

The empirical power model developed by Kucera and Mattson (1987) uses a power function to relate the depth of the corrosion pit with pipe age. A moderate nonlinear relationship between pit depth and pipe age is exhibited for the first 50 years of pipe life and this relationship is stabilized as a linear function thereafter. This model can be defined as:

$$d^* = K_a T^{n_a} \qquad (1.3)$$

Rossum (1968) proposes a general empirical power function that relates corrosion pit depth with pipe age to predict the remaining wall thickness of cast iron pipe. This equation is a function of corrosion pit depth, pipe age, soil pH, soil resistivity, and pipe surface area exposed to corrosion. There have not been many documented studies that validate Rossum's (1968) Power function. This model is defined as:

$$d^* = K_n C_{r(ext)}{}^{n} \qquad (1.4)$$

Where

$$C_{r(ext)} = [\frac{(10 - pH)T}{\rho_{soil}}] \qquad (1.5)$$

The first three of these models are developed and validated based on a data set collected from utilities across North America including the Cities of Edmonton, Winnipeg, Quebec, Boston, and Philadelphia. Figure 1.2 shows a plot of the corrosion pit depth versus pipe age for these models based on the data collected from these utilities (adapted from Sadiq et al. 2004).

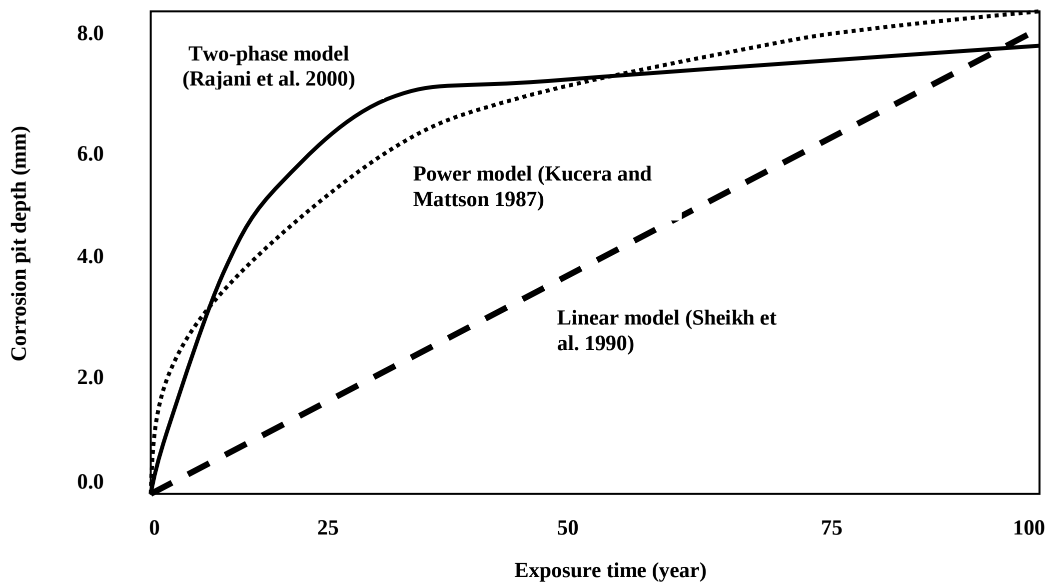

Figure 1.2. Comparison of predictive models for corrosion pit depths
(Adapted from Sadiq et al. 2004)

The choice of a particular model largely depends on the available data for a specific case and whether these data can be accurately described with one of the external corrosion models.

1.2.6.2 Internal corrosion models

Internal corrosion may be considered as a self-inhibiting process whereby the protective properties of corrosion products, i.e., generally iron-oxides, reduce the corrosion rate throughout the exposure time, e.g., within 18 months in cast iron (Snoeyink and Wagner 1996), and then stabilize the rate at a constant value thereafter.

Chlorine decay modeling in distribution systems is based on the consumption of chlorine due to the oxidation reactions within the bulk water, a first-order reaction, and to the oxidation reactions occurring at the pipe wall, a first or zeroth-order reaction. A theoretical zeroth-order model which defines the relationship between the chlorine decay rate and the corrosion rate is developed by Kiene and Wable (1996). This model is defined as:

$$-\frac{d[Cl_2]}{dt} = K\frac{C_{r(\text{int})}}{D} \tag{1.6}$$

A study regarding the relative importance of parameters influencing chlorine consumption in distribution systems by Kiene et al. (1998) shows that the corrosion of cast iron pipes is one of the major parameters. They undertake a pilot-scale study to determine the relationship between the free chlorine decay rate and corrosion rate under practical experimental conditions. They verify Equation 1.6 with values of K (chlorine decay constant) which are different from the theoretical value.

1.2.7 Internal and external stresses

Internal loads and external loads may cause stress in both the circumferential and longitudinal directions. Ahammed and Melchers (1994) show that if a pipe is uniformly loaded and supported along its length, then circumferential stresses can dominate. A large number of parameters influence the loads acting on pipe walls including the width of the trench, the unit weight of the soil, and the surface load.

Rajani et al. (2000) develop a model of external and internal stresses including all circumferential and longitudinal stresses. They define the hoop or circumferential stress as a combination of stresses due to internal fluid pressure, soil pressure, frost pressure, and traffic loads. Similarly the axial or longitudinal stress is defined as a combination of stresses related to internal fluid pressure, soil pressure, frost pressure, traffic loads, and pressure gradients due to temperature differences along the pipe. In this research, the overall likelihood of pipe failure over time is determined under the assumption that the pipe is uniformly loaded in the circumferential direction and supported along its length.

1.2.7.1 Circumferential stresses

Rajani et al. (2000) develop the following formulation for total circumferential stress as:

$$\sigma_\theta = \sigma_F + \sigma_S + \sigma_L + \sigma_V \qquad (1.7)$$

Where

$$\sigma_F = \frac{p_i \cdot D}{2 \cdot t_p} \qquad (1.8)$$

$$\sigma_S = \frac{3 \cdot K_m \cdot \gamma \cdot B_d^2 \cdot C_d \cdot E_p \cdot t_p \cdot D}{E_p \cdot t_p{}^3 + 3 \cdot K_d \cdot p_i \cdot D^3} \qquad (1.9)$$

$$\sigma_L = f_{frost} \times \sigma_S = f_{frost} \times \frac{3 \cdot K_m \cdot \gamma \cdot B_d^2 \cdot C_d \cdot E_p \cdot t_p \cdot D}{E_p \cdot t_p^{\ 3} + 3 \cdot K_d \cdot p_i \cdot D^3} \quad (1.10)$$

$$\sigma_V = \frac{3 \cdot K_m \cdot I_c \cdot C_s \cdot F \cdot E_p \cdot t_p \cdot D}{A \cdot [E_p \cdot t_p^{\ 3} + 3 \cdot K_d \cdot p_i \cdot D^3]} \quad (1.11)$$

Figure 1.3 shows the circumferential failure mode due to environmental and operational loads acting on a pipe segment. The effect of internal fluid pressure is significant compared with environmental pressures for determining circumferential stress.

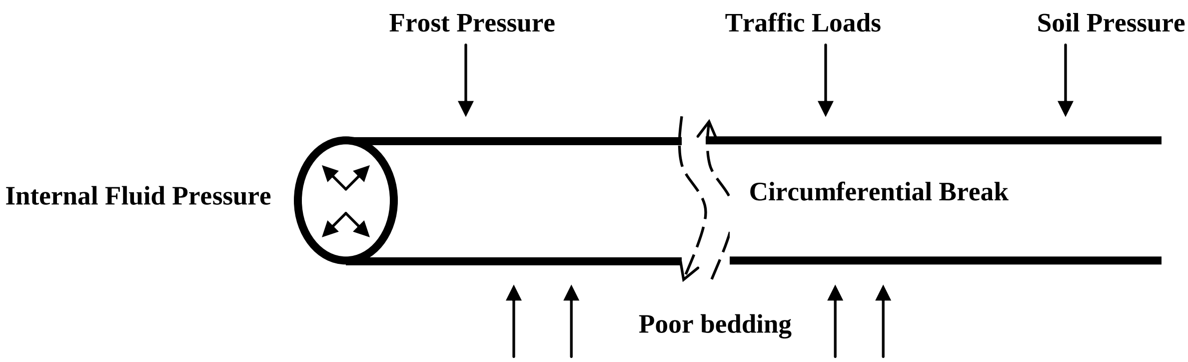

Figure1.3. Circumferential failure mode for cast iron pipe

1.2.7.2 Longitudinal stresses

Rajani et al. (2000) develop a formulation for total longitudinal stresses as:

$$\sigma_X = (\sigma'_F + \sigma_S + \sigma_L + \sigma_V)\nu_P + \sigma_T \quad (1.12)$$

Where

$$\sigma'_F = \left(\frac{p_i \cdot D}{2 \cdot t_p} - \frac{p_i}{2}\right) \quad (1.13)$$

$$\sigma_T = -E_P \cdot \alpha_P \cdot \Delta T \quad (1.14)$$

Figure 1.4 shows the axial failure mode resulting from longitudinal stresses. The effect of internal fluid pressure is minor compared with environmental pressures. The pressure gradient due to temperature differences along the pipe is significant for determining longitudinal stress.

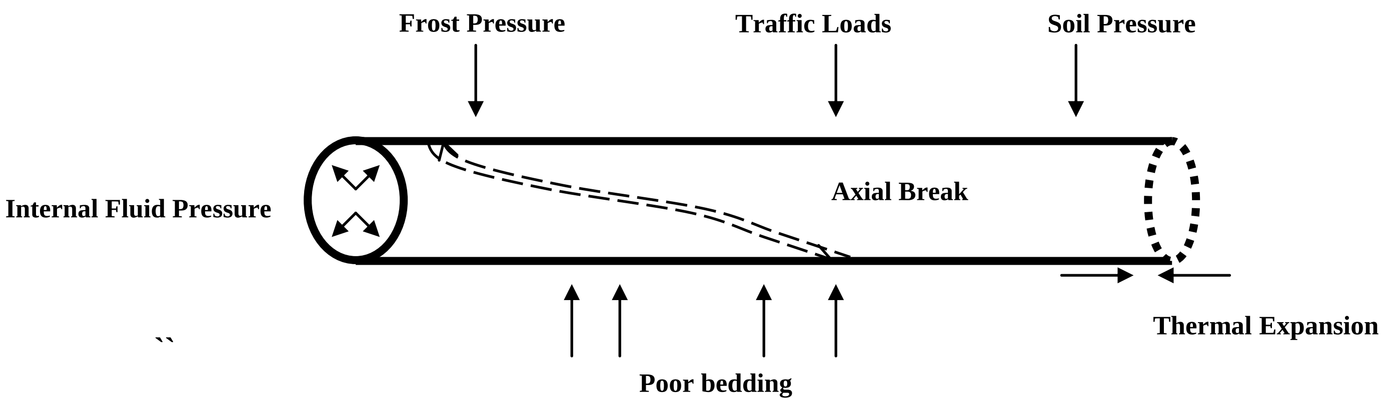

Figure 1.4. Longitudinal failure mode for cast iron pipe

1.2.8 Pipe strength capacity

Rajani et al. (2000) establish that the structural strength capacity, σ_Y , of cast iron is related to the corrosion pit depth. They show that increasing corrosion pit depth caused decreased pipe residual strength over exposure time. This model is described by the following relationship:

$$\sigma_Y = \frac{\alpha \cdot K_q}{\beta \cdot (d^*/t_{res} \cdot \sqrt{a_n})^S} \qquad (1.15)$$

Residual pipe thickness is defined as:

$$t_{res} = t_p - d^* \qquad (1.16)$$

1.3 PROBABILITY OF FAILURE ESTIMATION

1.3.1 Probability of failure definitions

Probability of failure is defined based on a load-resistance interference represented by a performance function *G*, which incorporates a set of random variables (*x*) and deterministic parameters. The performance function of a pipe segment is defined as the difference between the "resistance," *R*, and "load," *L*. The "resistance" is the strength or capacity of the system, e.g., a maximum acceptable decrease in the thickness of the pipe; whereas the "load" is the result of external conditions or influences upon a system, e.g., the corrosion depth.

States of the performance function may have more, but typically consist of two categories, safety ($G>0$) or failure ($G\leq0$). The boundary between both states corresponds to the surface in which random variables cause $G=0$ called limit-state surface. The probabilistic x-space is then categorized into two domains, i.e., the failure domain F where $G\leq 0$, and the safety domain S where $G>0$. The likelihood of being an event is in a safe domain S is referred to as reliability. The complement of reliability is known as the probability of failure. The exact probability of failure may be obtained by an analytical method using integration of joint probability density function, $f(x)$, over the failure domain or the event in which $G<0$ as follows:

$$P_f = \int_F f(x) \cdot dx \qquad (1.17)$$

The Equation 1.17 is the direct integration method. The exact probabilistic distribution of G may be derived based on $f(x)$. Analytical methods to estimate the probability of failure are generally impractical because either $f(x)$ or the derived distribution is not easy to estimate.

Different methods for estimating the probability of failure include 1) sampling methods such as those based on Monte Carlo Simulation (MCS); 2) approximate methods based on calculation of a point estimate of a performance function or a reliability index, β, such as First Order Reliability Method (FORM) and the Second Order Reliability Method (SORM); 3) combinations of FORM and SORM; and 4) FORM or SORM with Importance Sampling (Schueller et al. 1989 in which only on the region of most importance (e.g., near the surface of G=0) are sampled, or investigated, in order to estimate the probability of failure. The reliability index, β, is the ratio of the mean of G and the standard deviation of G. (Ang and Tang 1984; Madsen et al. 1986; Tung 1996; Melchers 1999; Lian and Yen 2003).

In this research, MCS, and FORM- and SORM-based approaches are used to estimate the probability of mechanical failure throughout the exposure time (T) due to the pipe corrosion. T is defined as the time period in which the pipe has been installed up to the time of analysis which corresponds to the pipe age.

1.3.1.1 Monte Carlo Simulation (MCS)

MCS is a sampling method in which a large number of simulations are performed using random variables to calculate the probability of events in the failure domain $G\leq 0$ and in the safety domain $G>0$. In MCS, multiple sampled values of x are randomly generated according to their respective probabilistic distributions. Then G is calculated for each set of generated sampled values. The statistics and a probabilistic distribution of G may be obtained based on the calculated values of G. If $G \leq 0$, then the combination of sampled random variables leads to the failure event. Similarly, the combination of sampled random variables leads to the probability of non-failure (reliability) where $G>0$. The probability of failure, P_f, may then be approximated by the ratio of the number of failure events, N_f, where $G<0$, and the total number of failure plus non-failure events, N, where $G \leq 0$ and $G>0$. It is defined as:

$$P_f = \frac{N_f}{N} \tag{1.18}$$

The larger the value of N, the more accurate the estimation of the probability of failure is. Despite their accuracy, sampling methods require high computational loads. Another drawback of this method is that it cannot be used to estimate the sensitivity of the reliability estimates to the various random variables.

1.3.1.2 First and Second Order Reliability Methods (FORM and SORM)

Approximations are efficient methods of estimating the probability of failure. The most practical approximation approaches are the reliability index-based methods (e.g., FORM and SORM) that approximate G using normally distributed and uncorrelated random variables.

Under a FORM analysis, the original x-space is transformed into a standardized uncorrelated normal space, u. Thus u-space has a zero mean and unit standard deviation. To simplify the solution, FORM transforms the original G in the u-space using the first-order Taylor Series expansion of G at the design point, u^*, as indicated in Figure 1.5. As a local optimum on the limit-state surface of G, u^* is the closest point to the origin of the u-space. If $G>0$, β is equal to the distance from the u origin to the limit-state surface at the design point u^*. For $G<0$, β is the negative of that distance between the u origin and the limit-state surface. Because u^* is a local optimum, the following relationship holds:

$$\beta = u^*. \alpha \tag{1.19}$$

Where α = the negative of the normalized gradient vector of G at u^*. FORM approximates P_f as follows:

$$Pf \approx \Phi(-\beta) \tag{1.20}$$

Where $\Phi(\ )$ = the cumulative distribution function of the standard normal distribution. Equation 1.20 implies that the reliability index is required to estimate the probability of failure. FORM has been shown to be adaptable for complex problems in comparison with the analytical method, and it is computationally efficient in comparison with MCS. In some complex problems where *G* is not linear, the first-order Taylor Series expansion of *G* may be inaccurate and may make estimating *u** difficult. Therefore, the robustness of FORM is decreased for these problems. FORM may be modified by assuming that the limit-state surface where *G=0* is a quadratic function with curvatures equal to those of the real limit-state surface at the design point *u**. The resulting method is called SORM.

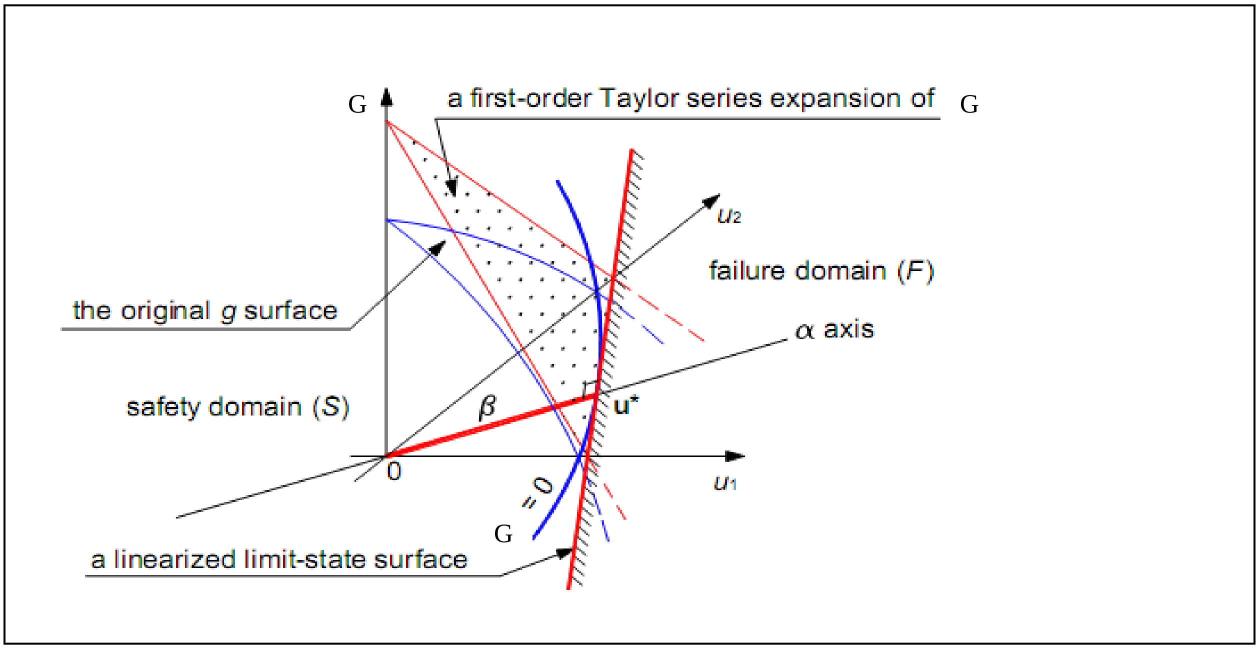

Figure 1.5 Schematic description of FORM in a bivariate *u*-space
(Adapted from Yi and Lence 2007)

In this research, an internal corrosion rate model is developed and combined with a Two-phase external corrosion model to estimate the effects of internal corrosion and probability of failure due to this throughout *T*. MCS, FORM-, and SORM-based approaches are used for this probability analysis. The efficiency of FORM-, and SORM- based approaches are evaluated herein.

One of the main advantages of FORM-, and SORM-based approaches is that they may be used to investigate the sensitivity of the overall probability of failure to each random variable. Sensitivity analysis is conducted to identify the variables that have the most significant effect on the reliability index, *β*, and subsequently on the probability of failure. The sensitivity of the reliability index to each of the random variables is evaluated by the rate of change of β with respect to each of the variables, and this is referred to as sensitivity factor, *n(x).* These rates are defined as the partial derivatives of β with respect to each of the variables as follows:

$$n(x) = \frac{\partial \beta}{\partial x} \tag{1.21}$$

1.3.2 Probabilistic models of pipe failure

Sadiq et al. (2004) estimate the reliability of a pipe in the face of external corrosion-associated failure in cast iron water mains. They define the failure time as the time at which the external stresses exceed the pipe strength capacity. They also define the performance function so as to relate all the parameters of the stresses acting on pipe, the pipe residual strength, and the external corrosion. The performance functions associated with circumferential stresses, *G (X)*, and longitudinal stresses, *G'(X)*, are expressed as Equations 1.17 and 1.18, respectively:

$$G(X) = \sigma_Y - \sigma_\theta \tag{1.22}$$

$$G'(X) = \sigma_Y - \sigma_X \tag{1.23}$$

Substituting Equations 1.8 - 1.11 in Equation 1.22 for considering circumferential stresses, Equations 1.9 - 1.11, 1.13, 1.14 in Equation 1.12 for considering longitudinal stresses, and then Equations 1.7, 1.12, 1.15 in Equations 1.22 and 1.23 for describing the performance function due to total circumferential, and to longitudinal stresses respectively, yields Equations 1.24 and 1.25, respectively:

$$G(X) = \frac{\alpha K_q}{\beta(d^*/t_p\sqrt{\alpha_n})^S} - \left[\frac{p_i D}{2t_p} + \frac{3K_m I_c C_s F E_p t_p D}{A\cdot[E_p {t_p}^3 + 3K_d p_i D^3]} + [1+f_{frost}] \times \frac{3K_m \gamma B_d^2 C_d E_p t_p D}{E_p {t_p}^3 + 3K_d p_i D^3}\right] \tag{1.24}$$

$$G'(X) = \frac{\alpha K_q}{\beta(d^*/t_p\sqrt{\alpha_n})^S} - \{[\frac{p_i}{2}(\frac{D}{t_p} - 1) + \frac{3K_m I_c C_s F E_p t_p D}{A.[E_p {t_p}^3 + 3K_d p_i D^3]} + [1+f_{frost}] \times \frac{3K_m \gamma B_d^2 C_d E_p t_p D}{E_p {t_p}^3 + 3K_d p_i D^3}]\upsilon_p - E_P \alpha_P \Delta T\} \tag{1.25}$$

For a given age of pipe, or time of exposure, if *G (X)* or *G'(X)* is less than zero, then the pipe is considered to have failed. The probability of failure, as in all reliability analyses, is defined as:

$$P(G) < 0 \quad \text{Or} \quad P(G^{'}) < 0 \qquad (1.26)$$

The effect of external corrosion on pipe mechanical failure is discussed extensively by Sadiq et al. (2004) but the effect of internal corrosion due to the variability in water quality parameters on the pipe mechanical failure is not addressed.

1.4 ASSET MANAGEMENT OF PIPE SYSTEMS

1.4.1 Asset management definitions

Vanier (2001) identifies six components of an asset management program. These are: asset inventory, asset value, deferred maintenance, asset condition, prediction of service life, and prioritization of repair and replacement of assets.

Inventory, as the first component of an asset management program, is the act of determining the type, quantity, and extent of the assets (e.g., water mains). In water resources management, the primary capital assets that are owned by utilities include water supply reservoirs, all hydraulic structures related to dams, water treatment plants, and water distribution systems with their components such as pipes, valves (e.g., pressure reducing valves), fire hydrants, tanks, pump stations, and meters. Computer tools such as spreadsheets, Geographic Information Systems (GISs), Computer Aided Drafting Systems (CAD), and Computerized Maintenance Management Systems (CMMSs) are used to track and maintain inventories of utilities. Wood and Lence (2006) report that archival records are still the predominant sources of data for utilities that serve the population of less than 50,000. Use of CMMs is growing in recent years but these systems are still expensive to implement and require significant resources to maintain (Wood 2007).

The total value of utility assets must be known to plan for replacement. Utility managers must have an overall understanding of the system worth and the budgetary needs for pipe replacement. In many utilities, in the case of estimating value for water mains, the value is simply estimated by multiplying an average cost of construction per meter of pipe by the total length of the pipes in the network (Wood 2007).

Asset management requires knowledge related to the condition of assets. Asset managers are facing problems associated with determining how and what to evaluate, defining what constitutes condition and indices, and determining how to use data related to condition of assets. There are no standard condition indices for assets (Grigg, 2004). A general diagnosis of the structural behavior of pipes is required, as are condition indices, to predict the pipe failure behavior over time and to improve the level of accuracy of pipe condition assessment that does not require a long history of data (De Silva et al. 2002). Also, field-based condition assessment is costly and only provides information for a pipe segment at a particular point in time. Therefore, the predicted number of pipe failures may be considered herein as one of the indicators for assessing the pipe condition and for undertaking the economic analysis to develop an asset management program.

The maintenance in water utilities that has not been performed or has been deferred is known as deferred maintenance. For deferred utility maintenance, the compounding effect of maintenance that has not been performed (e.g., not cleaning or repairing pipes) must be identified and managed. It is very difficult to quantify the deferred maintenance and there is very little information available for municipalities regarding deferred maintenance of water distribution systems (Wood 2007).

Estimating the service life of the pipes and undertaking long term planning for their replacement depends on prediction of the future conditions of the assets (e.g., water mains) in the system. To manage water utility assets and plan for replacement, the estimates of technical and economical service life of the assets is required. Rajani and Makar (2000) define the time of death of a pipe segment as the time in which its mechanical factor of safety is less than an acceptable value set by the utility manager. Kleiner and Rajani (1999) propose that the service life of a pipe segment is a function of the costs of deterioration rate and replacement and suggest that pipe failure coincides with the optimal time of replacement.

Prioritization of asset replacement is the last component of an asset management program. In this stage, managers should be able to determine what to replace and when to replace it. These are related to the financial and technical issues that lead to the decisions of whether or not to repair or replace an asset. Utilities have prioritized pipe replacements based on a combination of current management practices and historical breakage data.

In this research, the likelihood of failure for a given residual pipe wall thickness at a given pipe age is estimated using probabilistic analysis and the number of predicted breaks are estimated using survival analysis. Theses may serve as surrogates for condition in developing a comprehensive replacement strategy and may be coupled with economic assessment models to analyze future asset management decisions.

1.4.2 Long-term planning for pipe replacement and condition assessment

The most expensive component of a water supply system is the water mains in the distribution network (Shamir and Howard 1979). Aging water mains, coupled with the environmental and operational loads due to continuous stresses acting on pipes, leads to the system deterioration. Resulting pipe breaks may, in turn, lead to potential contamination of the water supply. Deterioration of a pipe network also increases operation and maintenance costs and water losses, and reduces the quality of service over time. Water utilities are facing the problem of maintaining deteriorating networks in the most efficient way possible to meet existing and future levels of service.

Give the system deterioration and potential shortages of future capital resources, it is essential to develop a comprehensive methodology to assist planners and decision- makers in selecting the most cost-effective rehabilitation policy that addresses the issues of reliability, safety, quality, and efficiency. That is, to assist them in undertaking long-term planning to maintain or improve water distribution system reliability and operation regularity within a specified budget.

Water distribution system replacement and rehabilitation has been the subject of research over the past two decades. Shamir and Howard (1979) apply regression analysis to obtain an exponential relationship for pipe breakage as a function of year of installation. This relationship is used to find the optimal time of pipe replacement at which the total cost of repair and replacement is minimized. Walski and Pelliccia (1982) propose a similar exponential relationship but add two other factors related to the historical pipe breaks and observed differences in breakage rates in larger diameter pipes. Walski (1987) adds the cost of water losses through pipe leakage and the cost of broken valve replacement to this decision model. In subsequent studies, the failure rate and the predicted number of pipe failures are used as essential parameters for undertaking an economic analysis as part of a long-term planning strategy

(Andreou et al., 1987a, b; Su and Mays, 1988; Kim and Mays, 1994; Schneiter et al., 1996). Failure rate corresponds to the instantaneous probability of having a break between time t and ($t+\Delta t$) conditional to survival up to time t.

Condition assessment and the prediction of system reliability are required to determine the long-term planning of the renewal of water distribution systems. It is defined as the readiness of the asset, e.g., the water main, to perform its function (Grigg, 2004).

Predictive modeling based on the statistical analysis of the recorded pipe breaks has been used in order to project future breaks (Andreou et al., 1987a, b). Survival analysis is the most common approach used for predicting pipe breakage behavior over the past two decades (Su and Mays, 1988, Andreou et al. 1987a; Kim and Mays, 1994). The statistically-based survival function, $S(T)$, presented by Kalbfleisch and Prentice (1980) is used to predict the behavior of breaks in a pipe segment throughout the exposure time. For example, the survival function associated with the Weibull distribution defined by two parameters, k and p, for describing the behavior of first break at time T, is defined as:

$$S(T) = \exp[-(kT)^p] \tag{1.27}$$

The hazard function (failure rate) is also used to estimate pipe breakage rate. It is the probability that a pipe experiences a failure between time T_1 and T_2 given that the pipe segment is operating at time zero and has survived to time T_1 (Kapur and Lamberson 1977). The hazard function is determined by Equation 1.28 that shows the relationship between the hazard function, the probability distribution function (PDF), $f(T)$, and cumulative probability function, $F(T)$, of pipe failure.

$$\lambda(T) = \frac{f(T)}{1 - F(T)} \tag{1.28}$$

Pelletier et al. (2003) estimate the hazard and survival functions for cast iron pipes using pipe break data for the municipalities of Chicoutimi, Gatineau and Saint-Georges, Quebec. They also determine the survival function for first breaks, based on their data. Pelletier (2000) and Mailhot et al. (2000) present a modeling strategy that uses the Weibull and Exponential distributions to model the different break orders. The Weibull distribution is associated with the behavior of first break and the Exponential distribution is used to describe the behavior of subsequent breaks.

The model developed by Pelletier (2000) requires an estimation of the PDF, hazard, and the survival functions. They estimate the number of pipe breaks for a given pipe segment between time T_1, and T_2, $\bar{n}(T_1, T_2)$, as:

$$\bar{n}(T_1, T_2) = [S(T_1) - S(T_2)] + k_2\{T_2[1 - S(T_2)] - T_1[1 - S(T_1)] - \int_{T_1}^{T_2} dt \times t \times f_1(T)\} \quad (1.29)$$

The likelihood of failure for a given residual pipe wall thickness is determined based on the results of the probability analysis due to the internal and external corrosion. The average number of pipe failures and the likelihood of failure for a given residual pipe wall thickness may then be considered as condition indices of water mains in water distribution systems.

1.5 CONTRIBUTIONS OF THESIS

The main contribution of this research is to link a variety of model applications including a chlorine consumption model, an internal corrosion rate model, internal and external corrosion rate models, a probability-based predictive pipe breakage model, and a model for estimating the total number of pipe failures, to determine a pipe condition assessment (e.g., condition indices) of water mains in water distribution systems. Data related to condition indices may be used to perform the economic evaluation for estimating an optimum replacement time for water mains that are failing as a result of both internal and external corrosion, and the budgetary needs for future repairs under various replacement and rehabilitation strategies as a part of asset management program.

The first contribution of this research is to use a chlorine consumption model (Kiene and Wable 1996) for developing an internal corrosion rate model that determines the relationship between water quality parameters (e.g., the chlorine concentration ratio) and hydraulic conditions (e.g., water velocity) with an internal corrosion rate, to estimate the probability of failure due to internal corrosion throughout the exposure time.

The second contribution is to use internal (Yamini and Lenc 2009) and external (Rajani et al. 2000) corrosion rate models to determine the overall probability of failure in water mains and to identify the variables that have the most significant effect on the probability of failure. All of the variables in internal and external corrosion models (e.g., the chlorine concentration ratio, and external corrosion scaling factor), environmental and operational loads (e.g., traffic loads, and water pressure), and pipe strength capacity (e.g., pipe thickness) are considered in the estimates of the probability of failure.

The third contribution of this research is to link the data resulting from the probabilistic analysis to a probability-based predictive pipe breakage model (Pelletier 2000; and Mailhot et al. 2000), and a total number of pipe failure model (Pelletier 2000) to estimate the two condition indices of water mains. This methodology integrates the probability of failure analysis with an appropriate probability-based predictive pipe breakage model, i.e., based on a Weibull distribution of first breaks and an Exponential distribution of subsequent pipe failures, to estimate the total number of pipe failures throughout the exposure time, as the first condition index of a pipe segment. The second condition index is defined as the likelihood of failure for a given residual pipe wall thickness at a given pipe age.

To validate the estimates of the survival function, which is based on the continuous probability density and hazard functions from the SORM analysis, the estimated survival function for all exposure times are compared with those determined by Pelletier et al. (2003) based on pipe break data for the municipalities of Chicoutimi, Gatineau and Saint-Georges, Quebec.

The primary contributions of this study is to link all the model applications to determine the probability of failure due to internal and external corrosion and to determine the two condition indices for understanding the structural behavior of water mains. A secondary contribution is the evaluation of the efficiency of FORM and SORM approximation approaches for this application.

1.6 STRUCTURE OF THESIS

This thesis is organized as a series of three manuscripts that have been submitted to or are tentatively accepted in journals. As a paper manuscript, each of the three chapters (Chapters 2 to 4) can be read and understood independently. Each of them contains a preface that links that chapter to the others, a main body, and references. In each of the chapters, figures and tables are embedded in the main body. All chapters adopt the reference style applied in American Society of Civil Engineers (ASCE) journals.

Chapter 2 introduces a method for estimating the probability of failure due to internal corrosion. This method employs a performance function based on the failure criteria assumed by the authors. A journal article manuscript resulting from this chapter has been accepted for publication in *ASCE Journal of Infrastructure Systems*, and is in print for December issue.

Chapter 3 discusses the expansion of this method for estimating the probability of failure due to internal and external corrosion and presents a comprehensive method for defining pipe failure at a given exposure time. A technical note resulting from this chapter was submitted to the *ASCE Journal of Infrastructure Systems*, was tentatively accepted for publication, and is in final review.

Chapter 4 proposes a methodology to evaluate the behavior of pipe breaks over time that may be used to estimate the condition of assets, i.e., water mains. This methodology integrates the failure probability analysis with an appropriate probability-based predictive pipe breakage model, i.e., based on a Weibull distribution of first breaks and an Exponential distribution of subsequent pipe failures, to estimate the condition of assets in a predefined planning period. This approach may be used to assist in long-term planning of pipe replacement in water distribution systems. A journal article manuscript resulting frok/m this chapter will be submitted to the *ASCE Journal of Infrastructure Systems*.

The final chapter, Chapter 5, presents the summary, conclusions, future work, and the limitation of the methods developed herein.

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CHAPTER 2

PROBABILITY OF FAILURE ANALYSIS DUE TO INTERNAL CORROSION IN CAST IRON PIPES

A version of this chapter has been accepted for publication in ASCE Journal of Infrastructure Systems. H. Yamini and B. J. Lence. Probability of Failure Analysis due to Internal Corrosion in Cast Iron Pipes.

PREFACE

In cast iron pipes, chlorine consumption due to internal corrosion is high compared with consumption caused by other water quality parameters in such systems, and may be considered as an approximate indicator of the rate of internal corrosion. In this chapter a methodology is developed for estimating the probability of mechanical failure of cast iron pipes due to internal corrosion.

A relationship is developed that determines the rate of internal corrosion as a function of the chlorine concentration ratio, chlorine decay constant, and the velocity of the water in a pipe segment with a given length and diameter. These parameters may be considered uncertain at any given time and the probability of mechanical failure due to internal corrosion of a pipe segment throughout the pipe life is thus estimated using probabilistic methods including Monte Carlo Simulation (MCS), the First Order Reliability Method (FORM)-, and the Second Order Reliability Method (SORM)-based approaches to account for these uncertainties. In this chapter a mechanical failure is defined as the point at which the corrosion depth is more than the maximum acceptable decrease in pipe wall thickness set by the utility manager. The results indicate that the likelihood of failure is nearly 50% by the 80^{th} year for a cast iron pipe of length 6.1 m and diameter of 203 mm, and that the affect of internal corrosion on mechanical failure is lower than the effect of external corrosion. Also, a sensitivity analysis is conducted to determine the sensitivity of the estimates of the probability of failure to each of the water quality and hydraulic conditions.

In the next chapter, an alternate failure mode is defined to estimate the probability of failure due to internal corrosion. Then the probability of failure due to both internal and external corrosion is estimated based on the environmental and operational imposed stresses acting on a pipe segment.

2.1 INTRODUCTION

Water distribution systems must be efficiently maintained, rehabilitated, and replaced to guarantee customers a sufficient supply of high quality and affordable water. The long-term planning of the renewal of pipes in water distribution systems requires assessment of the system reliability and estimation of the time to failure (Andreou et al., 1987a, b).

A large portion of the total pipe length in water distribution systems in Canada and the USA are aging cast iron pipes. A survey of 21 cities representing 11% of the Canadian population, conducted by Rajani and McDonald (1995), reveals that in 1993 approximately 50% of all water distribution pipes are gray cast iron. Kirmeyer et al. (1994) also report that 48% of water distribution pipes in the USA are gray cast iron. These pipes are also the oldest pipes, and have a tendency to corrode externally and internally under aggressive environmental conditions.

External corrosion can lead to the development of corrosion pits that may reduce the resistance capacity of the pipe segment, resulting in mechanical failure. The internal corrosion of pipes in distribution systems may lead to two major problems. Mechanical failure may result in water leakage and build up of corrosion products, i.e., scale layers, which may cause loss of hydraulic capacity. The second problem is the change in water quality as water travels through corroding pipes in the distribution system. This impact is caused by corrosion products entering the water, causing for example, red water.

Major lifetime costs of water distribution are the costs of the loss of water and of the pipe repairs needed to prevent leaks. The most effective methods of preventing corrosion in water mains include the application of surface coatings and the addition of inhibitors, e.g., chromate, nitrate, and phosphate, to control the internal corrosion (Snoeyink and Wagner 1996), and the application of surface coatings and the use of cathodic protection to control the external corrosion (Baeckmann et al.1997).

Kiene and Wable (1996) conduct an extensive series of laboratory studies at Lyonnaise des Eaux (LDE) in France directed toward understanding chlorine decay in a cast iron pipe. Based on these studies, they develop a general zeroth-order function that relates the ratio of chlorine concentration, i.e., the ratio of current chlorine concentration and the initial chlorine concentration, with the rate of internal corrosion in pipe segments. In a subsequent study, Kiene et al. (1998) and Zhang et al. (2008) identify the relative impact of a number of factors, including

Total Organic Carbon (TOC), initial free chlorine concentration, internal corrosion of iron pipes, and the amount of fixed biomass, on the degree of chlorine decay in water distribution pipes. They conclude that the chlorine consumption in uncoated cast iron pipes due to internal surface corrosion is high compared with the other water quality factors and therefore the corrosion of cast iron pipe is a major factor in chlorine decay in such pipes. Snoeyink and Wagner (1996) report on a laboratory study that show that while the rate of corrosion may be high when a cast iron pipe is installed, it decreases to a stable value within 18 months.

This chapter determines the probability of mechanical failure due to the thinning of the pipe wall caused by internal corrosion in cast iron pipes. This probabilistic analysis identifies and incorporates the relationships between water quality factors, e.g., chlorine concentration ratio, hydraulic performance, e.g., velocity, and the rate of internal corrosion. The probability of mechanical failure for a given exposure time may then be considered as one measure of pipe condition and incorporated into the planning of rehabilitation and replacement of pipes in water distribution systems.

MCS and FORM- and SORM-based approaches for estimating the probability of mechanical failure due to thinning of the pipe wall caused by internal corrosion are used herein. The most basic and accurate method is the MCS, while perhaps the most efficient are approximate methods such as those based on FORM and SORM. One of the requirements for using the FORM method is the linearity or near linearity of the performance function. The accuracy of FORM is influenced by the nonlinearity of the performance function but SORM does not suffer the same problem. While the primary contribution of this study is the development of the performance function that describes the probability of mechanical failure as a function of pipe wall thickness due to internal corrosion, a secondary contribution is the evaluation of the efficiency of these approximation approaches.

In the following two sections, a zeroth-order chlorine decay model developed by Kiene and Wable (1996) that describes the relationship between chlorine concentration ratio and the rate of internal corrosion, and the assumed linear relationship between the rate of internal corrosion and the corrosion depth (based on observations made by Snoeyink and Wagner 1996), are reviewed. The corrosion depth is estimated based on the assumption that the rate of corrosion is constant throughout the exposure time, at least when the pipe is more than 18 months old. Next, a performance function is developed that defines mechanical pipe failure as a case in which the pipe wall corrosion depth, which is a function of the chlorine concentration ratio and the rate of internal corrosion, is less than or equal to the allowable reduction of the pipe wall thickness. A probability of failure analysis is then conducted using this performance function for two different allowable pipe reduction criteria, and two pipe diameters. The importance of the variable distributions is also investigated.

2.2 CHLORINE DECAY -CORROSION RATE MODEL

Chlorine decay modeling in distribution systems is based on the consumption of chlorine due to the oxidation reactions within the bulk water, a first-order reaction, and to the oxidation reactions occurring at the pipe wall, a first or zeroth-order reaction (Vesconselous et al. 1996). Reduction of the chlorine residual is the most common water-quality concern and is a function of time of travel from the chlorine source, initial chlorine concentration, chlorine decay constant, and the rate of internal corrosion. Since the amount of exposed surface area of the pipes in a distribution system is large compared with the volume of water traveling through the pipes, the effect of the pipe wall reactions on chlorine decay is normally significant. Corrosion is the oxidation of metallic iron (Fe^0) to ferrous iron (Fe^{2+}) as shown in Equation 2.1.

$$Fe^0 \rightarrow Fe^{2+} + 2e^- \tag{2.1}$$

The intensity of the internal corrosion is controlled by the physical-chemical conditions in the pipe network such as the water temperature, pH, carbonate balance, and chlorine concentration and the presence of biofilm (Barbier at al. 1990). At temperatures and pH values common in water supply distribution networks the ferrous iron may reduce the chlorine concentration.

When free chlorine, Cl_2, is dissolved in water, it reacts rapidly to form hypochlorous, *HOCl*, and hydrochloric acid, *HCl*. Because hypochlorous acid is a stronger oxidant than hydrochloric acid under temperatures and *pH* values common in water distribution networks, it is considered as the main oxidant of ferrous iron as indicated in Equation 2.2.

$$2Fe^{2+} + HOCl + H^+ \rightarrow 2Fe^{3+} + Cl^- + H_2O \tag{2. 2}$$

Kiene and Wable (1996) propose a theoretical zeroth-order rate model for chlorine decay that is a function of the corrosion rate, assuming that the corrosion reaction is limited by the production rate of ferrous iron, Fe^{2+}, and that the free chlorine is the only oxidant of ferrous iron, i.e., *HOCl* is the main oxidant. This model is:

$$-\frac{d[Cl_2]}{dt} = K\frac{C_r}{D} \qquad (2.3)$$

Where $-\frac{d[Cl_2]}{dt}$ is the rate of chlorine decay.

Kiene, et al. (1998) undertake a pilot-scale study to determine the relationship between chlorine concentration ratio and the corrosion rate under typical field conditions to verify the theoretical model as indicated in Equation 2.3. According to these pilot-scale experiments, the chlorine concentration due to the corrosion process could be modeled based on the integration of Equation 2.3:

$$\frac{C_t}{C_0} = 1 - \frac{K}{C_0}\frac{C_r}{D}t \qquad (2.4)$$

All the experiments conducted by Kiene et al. (1998) confirm that chlorine concentration, C_t, can affect the internal corrosion rate considerably, and verify that a zeroth-order relationship, e.g., Equations 2.3 and 2.4 is representative of the reactions that occur in gray cast iron. The best-fit value of the experimental chlorine decay constant, *K*, from these experiments is 1.36 * 10^{-6} min^{-1}, about twice the theoretical value (Kiene et al. 1998). However, estimates of *K* and the ratio of chlorine concentration, $C_t /C0$, vary among different studies. Several factors may cause such differences and the most important of theses are: 1) inaccurate measurement of the corrosion rate in experimental studies, 2) variation in water quality and hydraulic conditions, and 3) the physical condition of the pipe examined (Kiene and Wable 1996). In this chapter, the chlorine decay constant, the ratio of chlorine concentration, and water velocity are considered to be uncertain values in the estimation of pipe wall thickness and thus in the probability of mechanical failure.

2.3 CORROSION MODELS

The loss of pipe wall due to the corrosion process can be either uniform around the pipe or localized. The corrosion phenomenon is complex, and the rate of wall loss due to both internal and external corrosion, as well as whether the rate is constant or variable, has been the subject of debate (Ahammed and Melchers 1994; Melchers 1996; and Snoeyink and Wagner 1996). In all cases, however, corrosion rate is generally considered to be high during early pipe ages and then stabilizes at a certain value thereafter. In the first phase a rapid growth of the corrosion pits occurs because any corrosion products formed on the pipe surface are porous and have poor protective properties. In the second phase a slow growth of the corrosion pits leading to a constant corrosion depth occurs due to the strong protective properties of the pipe. This complexity of the corrosion phenomena leads to the different corrosion models and different suggested definitions of corrosion based on the different assumptions made by researchers. Corrosion has been defined in terms of weight loss of the pipe material, maximum corrosion depth, or average corrosion depth (Ahammed and Melchers 1994).

In this chapter, a uniform corrosion process with a constant rate is assumed since over a long period, i.e., in old pipes, the localized corrosion pits grow to the point where they are in contact with one another, making individual sites of tuberculation indistinguishable and causing the pipe to appear to have a uniform layer covering the surface (Benjamin et al. 1996). Therefore, a linear corrosion model is employed for determining the corrosion depth, d^*. Considering a time of exposure, T, which represents the age of the pipe, the relationship between the internal corrosion rate and the corrosion depth, is assumed to be:

$$Cr = \frac{d^*}{T} \tag{2.5}$$

In practice, layers of corrosion products may accumulate on the pipe surface, and the variation in hydraulic conditions may cause sloughing of the corrosion products. Thus the corrosion depth may vary commensurately. Sloughing effects are not modeled herein.

2.4 PROBABILISTIC ANALYSIS

In this study, the mechanical failure due to internal corrosion is defined to occur when the corrosion depth is more than the maximum acceptable decrease in pipe wall thickness set by the utility manager. The performance function of a pipe segment is defined as the difference between the "resistance", *R*, and "load", *L*. The "resistance" is the strength or capacity of the system, e.g., a maximum acceptable decrease in the thickness of the pipe; whereas the "load" is the result of external conditions or influences upon a system, e.g., the corrosion depth. The corrosion depth may be estimated as a function of known factors, such as pipe diameter and length, and random variables, such as the chlorine decay constant and water velocity. The performance function, *G(X)*, may be expressed in terms of these random variables, *x*, as:

$$G(X) = R - L \tag{2.6}$$

The maximum acceptable decrease in the pipe thickness is selected by utility managers to determine the failure point in the pipe segment. In this study, two criteria for the failure point are examined to evaluate the probability of failure of the pipe throughout the exposure time. If the pipe thickness is represented as t_p, these criteria are expressed as $d_p=t_p/2$ and $d_p=t_p/4$, where d_p is the maximum acceptable decrease in pipe thickness defined by the difference between the outer, D_0, and inner, D, pipe diameters, $(D_0-D)/2$. Figure 2.1 shows a section of a pipe segment with its outer and inner diameters, and its pipe thickness.

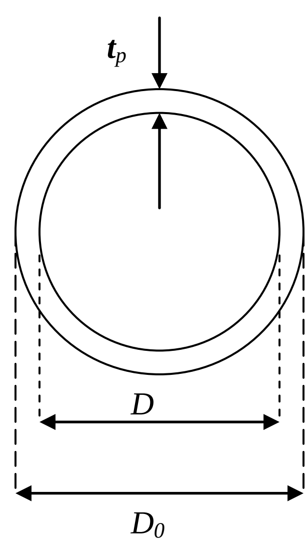

Figure 2.1. Section of a pipe segment with outer and inner diameters

The load used in the performance function is the corrosion depth determined by Equation 2.5 rearranged as:

$$d^* = C_r T \tag{2.7}$$

Equation 2.4 can be written in terms of C_r as follows:

$$C_r = C_0 (1 - \frac{C_t}{C_0}) \frac{D}{K} \frac{1}{t} \tag{2.8}$$

The ratio of the length of the pipe and the velocity of water may be substituted for travel time in Equation 2.8 to explicitly account for the hydraulic conditions of the system. Thus, Equation 2.8 may be expressed as:

$$C_r = C_0 (1 - \frac{C_t}{C_0}) \frac{D}{K} \frac{V}{L} \tag{2.9}$$

For the failure criterion in which the maximum acceptable decrease in pipe wall thickness is $t_p/2$, the performance function may be expressed as:

$$G(X) = \frac{D_0 - D}{4} - d^* \tag{2.10}$$

Substituting Equations 2.7 and 2.9 in Equation 2.10 yields:

$$G(X) = \frac{D_0 - D}{4} - [C_0 (1 - \frac{C_t}{C_0}) \frac{D}{K} \frac{V}{L}] T \tag{2.11}$$

For a given age of pipe or time of exposure, if *G(X)* is less than zero, then the pipe is considered to have failed and the probability of failure occurring is:

$$P(G) < 0 \tag{2.12}$$

In this analysis, random variables are considered to be chlorine decay constant, *K*, the water velocity, *V*, and the ratio of chlorine concentration, C_t/C_0, which represents the concentration of chlorine as water travels through the pipe. MCS and FORM- and SORM-based approaches are applied to estimate the probability of failure. While MCS is the most accurate method, the FORM- and SORM-based approaches are also examined to investigate the effect of nonlinearity of the performance function on estimates of the probability of mechanical failure. Here, the latter method is expected to perform better than the former method in highly nonlinear cases.

The probability of failure is estimated for a 6.1 m length of 203 and 548 mm diameter pipe throughout the exposure time. The pipe wall thickness prior to corrosion is considered to be 12 and 20 mm, for the 203 and 548 mm diameter pipes, respectively. The initial chlorine concentration is assumed to be 1 mg/l.

The probability of mechanical failure may be useful in identifying the remaining service life and in addressing long-term planning for the rehabilitation and replacement of water mains in distribution systems. Therefore, the time of exposure examined in this study is 10-200 years, i.e., T=10-200 in Equation 2.5. The starting point of 10 years is well above the 18 month period reported by Snoeyink and Wagner (1996) in which rapid corrosion occurs, allowing for the rate of corrosion to be stabilized at a constant value.

Often data required to define probability distribution functions (PDFs) are not available. Therefore, pre-defined distributions based on limited information are considered. Table 2.1 summarizes the subjectively derived probability distributions for the input variables used in this study (obtained from Keine et al. 1998; and Mays 2000). Statistical distributions such as the Normal, Lognormal, and Gumbel distributions are examined to show how these distributions may affect the probability of failure at a given exposure time. All probability estimates are determined using the Relan software, Version 7 (Foschi and Li 2005).

Table2.1. Characteristics of input variables for the probabilistic model of pipe failure

Pipe diameter	Parameter	Source	Minimum	Mean	StdDev.	Maximum
548 mm	Chlorine concentration rate, Ct/C0	Mays, 2000	0.89	0.94	0.04	0.99
	chlorine decay constant (mg/l), K	Kiene et al., 1998	6.32×10^{-7}	1.01×10^{-6}	0.34×10^{-6}	1.36×10^{-6}
	Water velocity (m/s), V	Mays, 2000	0.6	1.3	0.6	2.0
203 mm	Chlorine concentration rate, Ct/C0	Mays, 2000	0.5	0.94	0.04	1.3
	chlorine decay constant (mg/l), K	Kiene et al., 1998	6.32×10^{-7}	1.01×10^{-6}	0.34×10^{-6}	1.36×10^{-6}
	Water velocity (m/s), V	Mays, 2000	0.6	1.8	0.5	2.7

The distributions of all input variables are assumed to be independent. However, in reality cases in which the variables are correlated are possible. For example, the ratio of chlorine concentration is related to the hydraulic conditions, e.g., water velocity, and the water velocity is also related to the pipe diameter (Menaia et al. 2003). In pipe networks, for smaller pipe diameter, the velocity of water is higher and the higher velocity of water may also increase the chlorine consumption as water travels through the pipe. Therefore, cases in which variables have a range of degree of correlation are examined to estimate the impact of this assumption.

2.5 RESULTS

The data in Figure 2.2 provide the results of the MCS, and FORM- and SORM-based approaches for a 203 mm diameter pipe, a failure criteria of $d^* \geq t_P / 2$, and normal distributions for all random variables. The difference in probability of failure is less than five percent in the first 50 years of exposure using the MCS, and FORM- and SORM-based approaches. The nonlinearity of the performance function leads to a substantial difference between the FORM and SORM-based results after the 50 years of exposure time. For this case, the SORM-based approach performs well for exposure times greater than 50 years. The likelihood of failure increases to nearly 50% in the 80th year of pipe age. This indicates that the effect of internal corrosion on pipe wall thickness and thus mechanical failure is lower than the effect of external corrosion on such failures. Sadiq et al. (2004) estimate a 50% likelihood of failure in the 70th year of pipe age in the case of external corrosion for the same type of pipe.

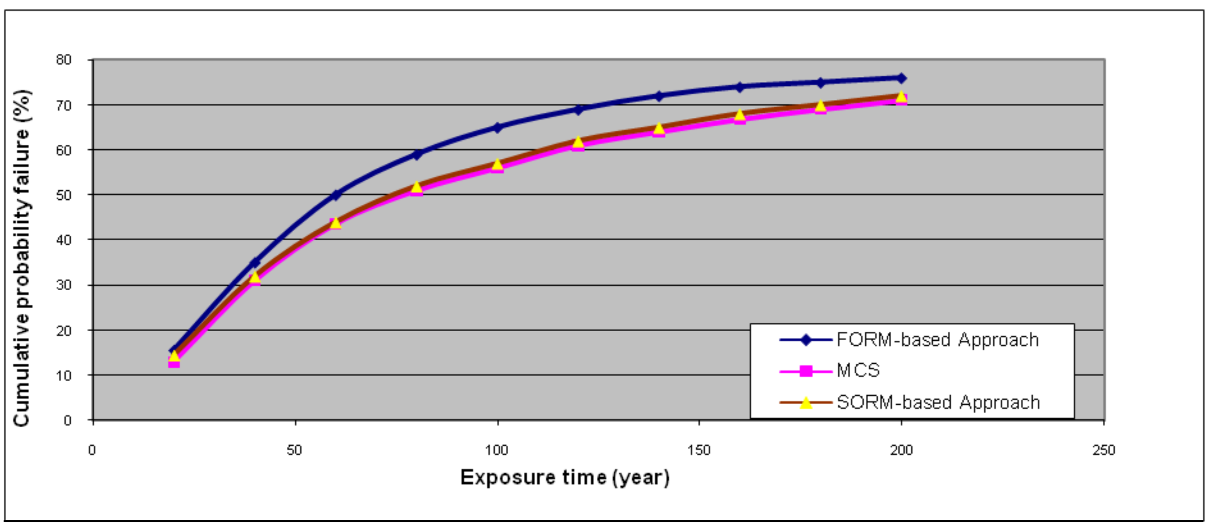

Figure 2.2. Probability of failure throughout the exposure time, for a normal distribution using MCS and FORM- and SORM-based approaches (203 mm pipe diameter and failure criteria of $d^* \geq t_P / 2$)

The data in Figure 2.3 provide the results of the SORM-based analysis using Normal, Lognormal, and Gumbel distributions for all random variables of the analysis for a 203 mm pipe diameter and the failure criteria of $d^* \geq t_P/2$. The results show that the maximum difference among these distributions is less than 15%. The probability of failure is less than 5% in the first 80 years of exposure under all distribution types.

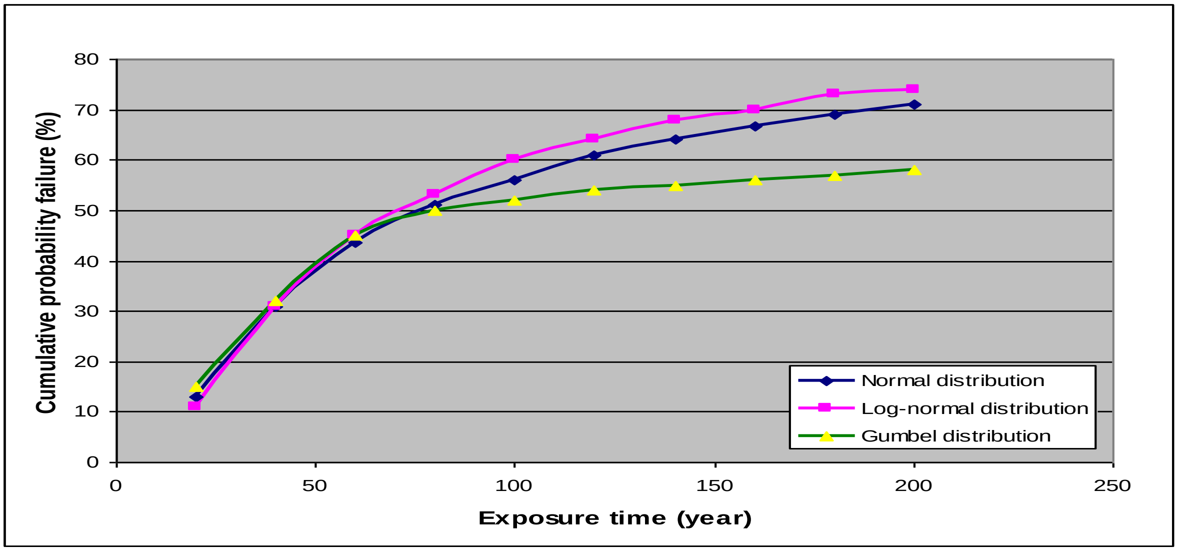

Figure 2.3. Probability of failure throughout the exposure time, for all statistical distributions using a SORM-based approach (203 mm pipe diameter and failure criteria of $d^* \geq t_P/2$)

The probability of failure is also estimated for a 548 mm pipe diameter for the failure criteria of $d^* \geq t_P/2$ and compared with the probability of failure for a 203 mm pipe diameter (see Figure 2.4). The results show that for the 548 mm pipe the probability of failure is 50% in the 90th year of exposure. The probability of failure is increased in smaller pipe diameters and this is likely due to the higher average velocities in such pipes.

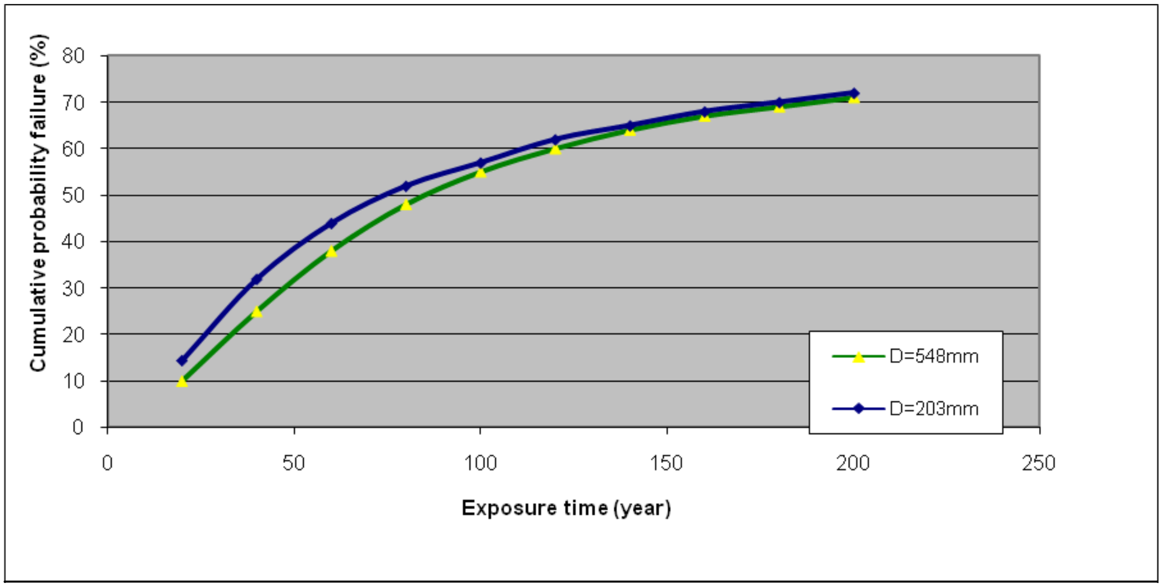

Figure 2.4. Probability of failure throughout the exposure time, for a normal distribution and various pipe diameters using a SORM-based approach (failure criteria of $d^* \geq t_P / 2$)

The data in Figure 2.5 show how the probability of failure varies throughout the exposure time for different failure criteria for a 203 mm pipe diameter. The results show that with maximum acceptable decreases of $d_p=t_p/2$ and $d_p=t_p/4$, the probability of failure is 50%, when the pipe is 80 years old and 38 years old, respectively.

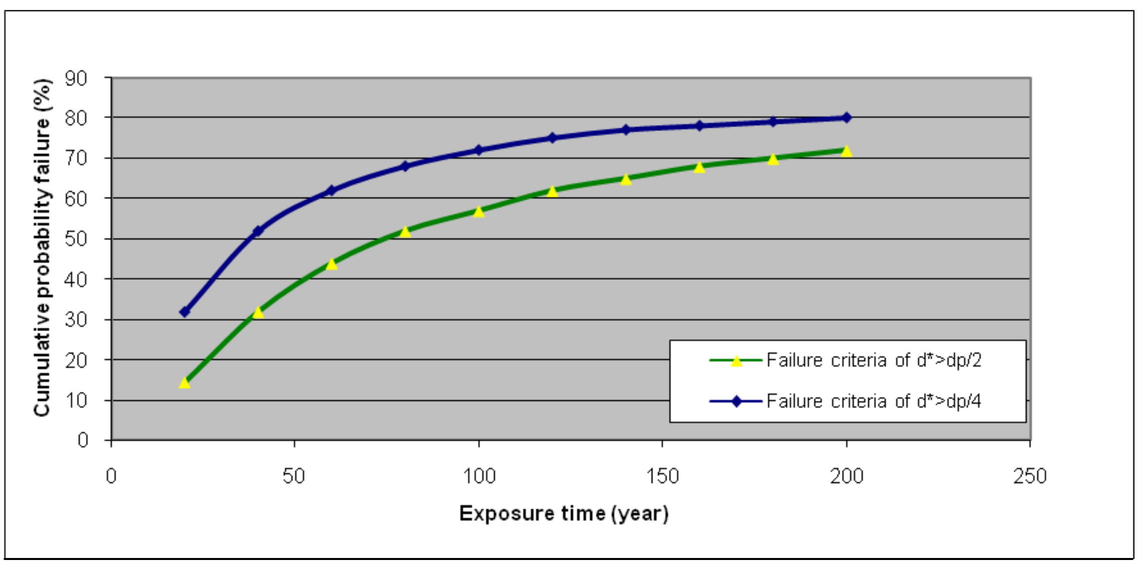

Figure 2.5.Probability of failure throughout the exposure time, for a normal distribution and two failure criteria using a SORM-based approach (203 mm pipe diameter)

The data in Figure 2.6 show the probability of failure throughout the exposure time assuming that all variables are uncorrelated, exactly correlated (correlation coefficient of 1.0) and somewhat correlated (correlation coefficient of 0.5). The results indicate that the maximum difference between probabilities based on these assumptions is less than 10%. When the variables are considered to be correlated, the random variables that are partially or highly correlated may counter balance each other and cause only a moderate variation in probability of failure at a given exposure time.

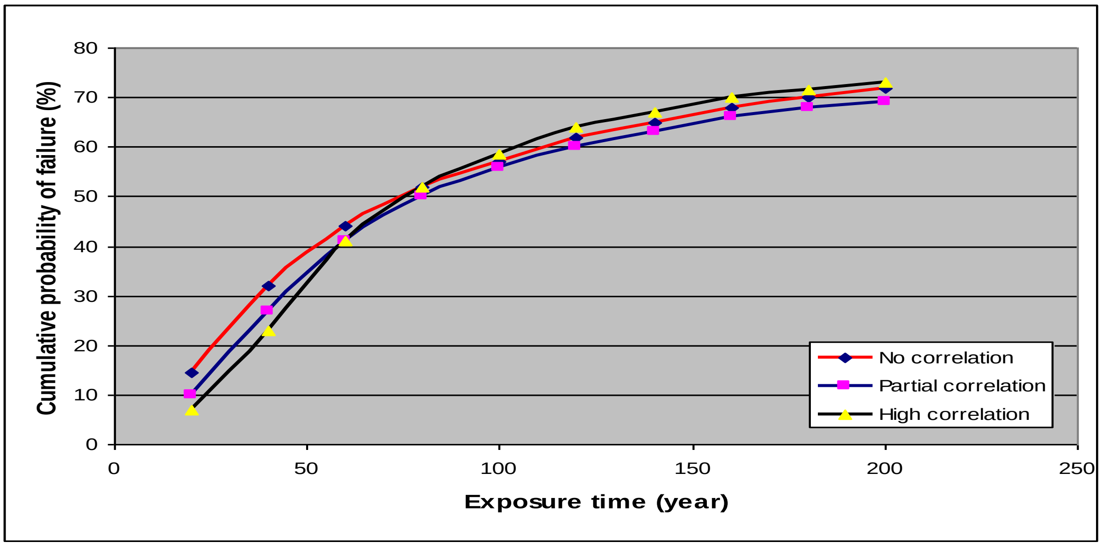

Figure 2.6. Probability of failure throughout the exposure time, for a normal distribution with different correlation assumptions using a SORM-based approach (203 mm pipe diameter and failure criteria of $d^* \geq t_P / 2$)

2.6 SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to identify the variables that have the most significant effect on the reliability index, β, and subsequently on the probability of failure. The sensitivity of the reliability index to each of the three variables (C_t /C_0, K, V) is evaluated by the rate of change of the β with respect to each of the variables, called the sensitivity factor. These rates are given as the partial derivatives of β with respect to each of the variables.

The sensitivity factors are determined using the Relan software, Version 7 (Foschi and Li 2005). The sensitivity factors for each of the three variables (C_t /C_0, K, V) are shown in Figure 2.7 for the range of exposure time. The results indicate that the sensitivity factor for the chlorine concentration ratio, C_t/C_0, is higher than that for any other variable in terms of their contribution to the probability of mechanical failure after 30 years of pipe age. This implies that the probability of failure is most sensitive to the ratio of chlorine concentration, C_t/C_0, which represents the current concentration of chlorine as water travels through the pipe and is dependent on the initial chlorine concentration and the rate of corrosion. Thus, the analysis of boosting chlorine throughout a system, its influence on the rate of corrosion and on the chlorine concentration ratio is recommended as a means of further extending pipe life.

Data in Figure 2.7 show that while the variable *K* has the most influence on the probability of failure before 30 years of pipe age, its importance is greatly reduced thereafter. The value of *K* represents the intensity of internal corrosion rate and should be examined carefully to show the real value of internal corrosion rate in the pipe segment.

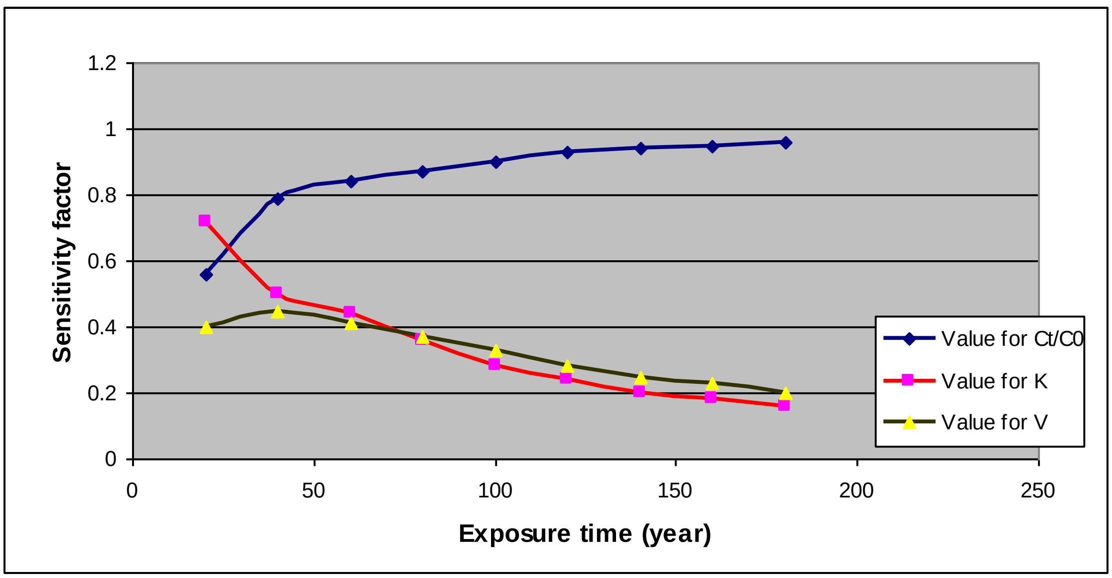

Figure 2.7. Sensitivity factors for input parameters throughout the exposure time, for a normal distribution using a SORM-based approach (203 mm pipe diameter and failure criteria of $d^* \geq t_p/2$)

The results also show that the velocity of water has a minimal effect on the probability of failure among these variables before 80 years of pipe age.

2.7 SUMMARY AND CONCLUSIONS

Chlorine consumption in cast iron pipe due to internal corrosion is high compared with other water quality factors including Total Organic Carbon, TOC, initial free chlorine concentration, and the amount of fixed biomass (Kiene et al. 1998). The internal corrosion of cast iron pipe may cause the loss of pipe wall and this is one of the major factors contributing to pipe mechanical failure. Considering the effect of internal corrosion on the pipe wall and thus mechanical failure, probabilistic analyses are used herein to estimate the probability of mechanical failure throughout the exposure time based on a zeroth-order model that represents the relationship between the chlorine decay and the internal corrosion rate. Using MCS and the SORM-based approach leads to more accurate estimates of the probability of failure compared with the FORM-based approach. Probability of failure throughout the exposure time is estimated for two different pipe diameters. The probability of failure is greater for smaller diameter pipes because the mean velocity is greater in such pipes. The sensitivity of the probability of failure to different variables is estimated to determine which variables have the most influence throughout the exposure time. Compared with the hydraulic performance, e.g., water velocity, the water quality factors, e.g., ratio of chlorine concentration and the chlorine decay constant, are the most important variables influencing the probability of failure.

Probability of failure for a given exposure time may be thought of as a surrogate for the service life of a pipe. This information may be useful in addressing the planning process for the rehabilitation and replacement of the system infrastructure.

The importance of the chlorine decay constant in modeling water quality has been extensively studied. The correct measurement of K should be determined to reflect the appropriate internal corrosion rate in the pipe network. Therefore, advances in infrastructure asset management may benefit from further analysis of the chlorine decay constant to determine the accurate internal corrosion rate in the pipe network.

The probabilistic analysis conducted in this work is based on the assumptions that the chlorine is the only oxidant of ferrous iron, Fe^{2+}, the internal corrosion rate is uniform and has a constant value throughout the exposure time, i.e., T=10-200, and water quality failure and sloughing effects are not modeled. The risk of failure may be further heightened if the water quality and sloughing effects are considered. Also, variation of the corrosion rate may cause significant changes in pipe failure results. These considerations should be investigated in future studies.

Further studies that may be beneficial include: expanding the performance function to include other modes of failure, most importantly water quality failure due to the release of corrosion products, e.g., contributing to red water; and undertaking probability analyses that include both internal and external corrosion. External corrosion has been shown to affect pipe wall and thus mechanical failure significantly and the risk of failure may be further heightened by internal corrosion. A sensitivity analysis can be conducted to determine the contribution of uncertain input variables of both external and internal corrosion to the variability of the time to failure. These analyses may be useful to determine a comprehensive method to assist in the development of future asset management strategies.

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CHAPTER 3

PROBABILITY OF FAILURE ANALYSIS DUE TO INTERNAL AND EXTERNAL CORROSION IN CAST IRON PIPES

A version of this chapter has been submitted for publication H. Yamini and B. J. Lence. Probability of Failure Analysis due to Internal and External Corrosion in Cast Iron Pipes.

PREFACE

In the previous chapter the probability of failure due to internal corrosion is estimated based on the criteria that a failure occurs when the corrosion depth is more than the maximum acceptable decrease in pipe wall thickness set by the utility manager. Internal corrosion may lead to water leakage and loss of hydraulic capacity caused by the loss of pipe wall thickness and build up of corrosion products which also reduce the resistance capacity of the pipe segment

External corrosion can also lead to the development of corrosion pits that may reduce the resistance capacity of the pipe segment to resist stresses upon a pipe segment. It has been shown to affect the pipe mechanical failure significantly. The risk of mechanical failure may be further heightened if internal corrosion is considered. This chapter develops a methodology for estimating the probability of mechanical failure of cast iron pipes due to both internal and external corrosion.

Two failure points are defined to estimate the probability of failure due to the internal corrosion and to both the internal and external corrosion. The first failure point is defined as the time at which the stress due to water pressure exceeds the pipe strength capacity considering only internal corrosion. The second failure point is defined as the time at which total stresses exceed the pipe strength capacity considering the effect of both internal and external corrosion.

Using the failure definitions allows for a comparison to be made with the failure definition for the probability of failure due to the external corrosion estimated by Sadiq et al. (2004). Each definition is based on the difference between the stresses acting on a pipe segment and the pipe strength capacity.

A probabilistic analysis is used that incorporates a linear internal corrosion model as well as the Two-phase nonlinear external corrosion model (Rajani et al., 2000) to calculate the probability of pipe failure. The Monte Carlo Simulation (MCS), and First Order Reliability Method (FORM)- and Second Order Reliability Method (SORM)-based approaches are used to perform the probabilistic analysis. The results indicate that the likelihood of failure of a cast iron pipe due to internal corrosion is nearly 50% by the 110th year of exposure and the likelihood of failure of a cast iron pipe due to both internal and external corrosion is nearly 50% by the 45th year of exposure. A sensitivity analysis is conducted to determine the sensitivity of the estimates of the probability of failure to each of the uncertain inputs of internal and external corrosion.

This analysis reveals that the contribution of external and internal corrosion parameters to the variability of time to failure is more significant than the contributions of other parameters.

In the next chapter, a methodology is developed to integrate the probability of failure analysis with an appropriate probability-based predictive pipe breakage model inspired by survival analysis to estimate the condition of assets in a predefined planning period.

3.1 INTRODUCTION

Cast iron pipes have been used to transfer potable water for more than 500 years, and iron pipe corrosion has been a problem for as long. Old cast iron pipes, which represent a large portion of the total pipe length in water distribution systems, as well as their financial cost to water utilities, have been the subject of extensive research over the past 20 years in Canada and the USA (Kirmeyer et al. 1994; Kleiner 1998; Selvakumar et al. 2002; Rajani and Tesfamariam 2005). These pipes have a tendency to corrode externally and internally under aggressive environmental conditions.

Corrosion of pipes is a major factor in the weakening of pipe integrity and leads to several problems, including pipe breaks, loss of hydraulic capacity, and poor water quality (Mays 2000). Water utilities in Canada and in the USA invest capital and operating funds to maintain the water mains of distribution systems. Much of this expenditure is to repair or replace ageing cast iron mains that have suffered from corrosion throughout the pipe exposure time. It is estimated that the financial costs for pipe repair and replacement exceeds $1 billion annually in Canada alone (Rajani and Tesfamariam 2005). Also, Selvakumar et al. (2002) report that the total costs of pipe repair and replacement exceeds $3.7 billion annually in the USA.

The most effective methods of preventing corrosion in water mains include the application of surface lining and addition of inhibitors, e.g., chromate, nitrate, phosphate, to control the internal corrosion (Snoeyink and Wagner 1996), and the application of surface coating and the use of cathodic protection to control the external corrosion (Baeckmann et al. 1997).

Corrosion of cast iron pipes in distribution systems can lead to the development of corrosion pits that may reduce the resistance capacity of the pipe segment, resulting in mechanical failure. The mechanical failure of pipes is mostly the result of this structural weakening due to externally, environmental, and internally, operational, imposed stresses and the vulnerability of pipes due to their structural properties, type of material, pipe-soil interaction, and inadequate pipe installation. Pipe vulnerability due to these latter processes has not been modeled because of the varied, uncertain, and complex factors involved.

This chapter develops a methodology to determine the probability of failure due to the thinness of the pipe wall caused by internal and external corrosion in cast iron pipes. This probabilistic analysis identifies and incorporates variables related to water quality, e.g., the chlorine decay rate, hydraulic performance, e.g., velocity and internal water pressure, and external stresses, e.g., stress due to soil pressure, and the rate of internal and external corrosion to estimate the probability of failure of a pipe segment. The probability of failure for a given exposure time may then be considered as one measure of condition and incorporated into the planning of rehabilitation and replacement of pipes in water distribution systems.

The high degree of uncertainty associated with factors that affect pipe failures warrants a probabilistic-based analytical approach. A detailed uncertainty analysis is required to quantify the probability of pipe failures at a given time.

MCS and FORM- and SORM-based approaches for estimating the probability of mechanical failure due to the thinness of the pipe wall caused by internal and external corrosion are used herein. While the primary contribution of this study is the development of the performance function that describes the probability of mechanical failure as a function of pipe wall thickness due to internal and external corrosion, a secondary contribution is the evaluation of the efficiency of these approximation approaches.

In the following two sections, the external stresses acting on a pipe segment and corrosion models are reviewed. Next, functions that describe the impact on pipe integrity of internal corrosion and both internal and external corrosion are defined.

Then performance functions that define mechanical pipe failure due to the thinness of the pipe wall caused by 1) internal corrosion as a case in which the stress due to water pressure exceeds the pipe strength capacity and 2) both internal and external corrosion as a case in which the total stresses, e.g., stresses due to internal water chemistry and pressure, soil, traffic, and frost pressures, exceed the pipe strength capacity, are developed. A sensitivity analysis which describes the importance of the variables related to internal and external corrosion, hydraulic performance, and all stresses acting on the pipe, is undertaken thereafter.

3.2 EXTERNAL AND INTERNAL STRESSES AND CORROSION MODELS

Internal, e.g., internal fluid pressure, and external, e.g., soil pressure, loads may cause stress in both the circumferential and longitudinal directions. Ahammed and Melchers (1994) show that if a pipe is uniformly loaded and supported along its length, then circumferential stresses may dominate. A large number of factors influence the loads acting on pipe walls including the width of the trench, the unit weight of the soil, and the surface load.

Rajani et al. (2000) develop a model of external and internal stresses including all circumferential and longitudinal stresses. They define the hoop or circumferential stress, σ_θ, as a combination of stresses due to internal fluid pressure, σ_F, soil pressure, σ_S, frost pressure, σ_L, and traffic loads, σ_V. Similarly the axial, or longitudinal, stress is defined as a combination of these stresses and pressure gradients, σ_T, due to temperature differences. They show that the effect of internal fluid pressure is minor compared with environmental pressures for determining longitudinal stress, while the effect of internal pressure is significant compared with environmental pressures for determining circumferential stress.

Rajani et al. (2000) develop the following formulation for total circumferential stress:

$$\sigma_\theta = \sigma_F + \sigma_S + \sigma_L + \sigma_V \tag{3.1}$$

Where

$$\sigma_F = \frac{p_i \cdot D}{2 \cdot t_p} \tag{3.2}$$

$$\sigma_S = \frac{3 \cdot K_m \cdot \gamma \cdot B_d^2 \cdot C_d \cdot E_p \cdot t_p \cdot D}{E_p \cdot {t_p}^3 + 3 \cdot K_d \cdot p_i \cdot D^3} \tag{3.3}$$

$$\sigma_L = f_{frost} \times \sigma_S = f_{frost} \times \frac{3 \cdot K_m \cdot \gamma \cdot B_d^2 \cdot C_d \cdot E_p \cdot t_p \cdot D}{E_p \cdot {t_p}^3 + 3 \cdot K_d \cdot p_i \cdot D^3} \tag{3.4}$$

$$\sigma_V = \frac{3 \cdot K_m \cdot I_c \cdot C_t \cdot F \cdot E_p \cdot t_p \cdot D}{A \cdot [E_p \cdot {t_p}^3 + 3 \cdot K_d \cdot p_i \cdot D^3]} \tag{3.5}$$

Rajani et al. (2000) recommend the consideration of frost pressure, which is approximately a multiple of 0 to1 (i.e., 0 to 100%) of the soil pressure. Seasonal variations in temperature may be the cause of the variation in frost pressure. Chapter 1, Figure 1.3 shows the circumferential forces acting on a pipe and the orientation of failures that may occur due to the environmental and operational loads.

A review of existing stress models (Rajani and Kleiner 1996; Rajani et al. 2000) for cast iron pipes in water distribution systems shows that the total circumferential stress model developed by Rajani et al. (2000) (Equation 3.1) is the most comprehensive models of pipe failure. This model incorporates most of the identified stresses that may act on a pipe segment. In this chapter, the effect of the loads in the circumferential direction is considered under the assumption that the pipe is uniformly loaded and supported along its length to estimate the overall likelihood of pipe failure.

Rajani et al. (2000) develop the Two-phase empirical corrosion model which is based on the assumption that the corrosion rate is generally high during early pipe ages and then stabilizes at a certain value thereafter. Figure 3.1 shows the form of the Two-phase external corrosion model as well as the linear internal corrosion model developed in Chapter 2. The model predictions are the relationship between external and internal corrosion depth, for the Two-phase and linear model, respectively, and the pipe exposure time.

During the first phase of the Two-phase external corrosion model, a rapid exponential pit growth occurs and in the second phase a reduced linear pit growth occurs due to the corrosion self-inhibiting process. This pit depth is defined as:

$$d*_{ext} = aT + b(1 - e^{-cT}) \tag{3.6}$$

This model is employed in this chapter to evaluate the probability of failure due to external corrosion throughout the exposure time.

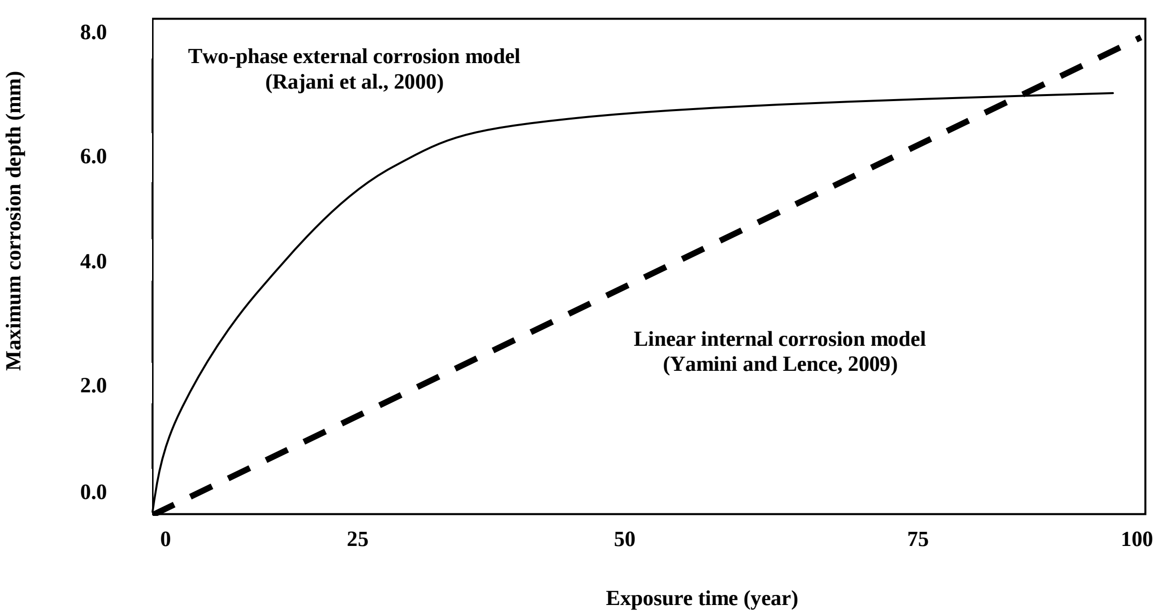

Figure 3.1. Predictive external and internal corrosion models for corrosion depths

In Chapter 2, an internal corrosion model is developed that relates the rate of internal corrosion to the ratio of chlorine concentration, i.e., the ratio of current chlorine concentration and the initial chlorine concentration as water travels through the pipe, chlorine decay constant, and the velocity of the water in a pipe segment with a 6.1 m length and 203 mm diameter. Figure 3.1 also shows a linear relationship between the corrosion depth caused by internal corrosion and the pipe exposure time. The internal corrosion model is defined as:

$$d^*_{\text{int}} = C_{r(\text{int})}T = [C_0(1 - \frac{C_t}{C_0})\frac{D}{K}\frac{V}{L}]T \quad (3.7)$$

In this work, corrosion models are used to determine the external, d^*_{ext}, and internal corrosion depth, d^*_{int}, which are in turn used to define the resistance capacity of the pipes. For convenience, in all equations related to stresses, the original pipe thickness, t_p, is replaced with residual pipe thickness (t_{res}) to calculate the probability of failure. The residual pipe thickness is defined as:

$$t_{res} = t_p - d^* \quad (3.8)$$

Where

$$d^* = d^*_{ext} + d^*_{\text{int}} \quad (3.9)$$

3.3 PIPE STRENGTH CAPACITY

Rajani et al. (2000) state that the structural strength capacity, σ_Y, of cast iron is related to the corrosion pit depth. They show that increasing the corrosion pit depth causes decreases in the pipe residual strength over the pipe exposure time. This model is described by the following relationship:

$$\sigma_Y = \frac{\alpha K_q}{a_1(\frac{d^*}{t_{res}})^{b_1}(d^*/t_{res}\sqrt{a_n})^S} \quad (3.10)$$

3.4 PROBABILITY OF FAILURE DUE TO INTERNAL CORROSION

The mechanical failure due to the thinness of the pipe wall caused by internal corrosion is defined as the case in which the stress due to water pressure exceeds the pipe strength capacity under the assumption that no environmental pressures affect the pipe failure throughout the exposure time. The performance function of a pipe segment is defined as the difference between the "resistance", *R*, and "load", *L*. The "resistance" is the strength or capacity of the system, e.g., a pipe strength capacity, whereas the "load" is the result of environmental and operational conditions on the system, e.g., stress due to water pressure. The performance function, *G(X)*, may be expressed in terms of random variables, *x*, as:

$$G(X) = R - L \tag{3.11}$$

The maximum acceptable stress may be selected by utility managers to determine the failure point in the pipe segment. In this chapter, two criteria for the failure point are examined to evaluate the probability of failure of the pipe throughout the exposure time. These are the points at which resulting resistance capacity due to 1) internal corrosion and 2) the combination of internal and external corrosion, are less than the loads on the system. For the first failure criterion in which the stress due to water pressure exceeds the pipe strength capacity, the performance function may be expressed as:

$$G(X) = \sigma_Y - \sigma_F \tag{3.12}$$

Substituting Equations 3.2 and 3.10 in Equation 3.12 and replacing t_p with t_{res}, yields:

$$G(X) = \frac{\alpha K_q}{a_1 (\frac{d*_{\text{int}}}{t_{res}})^{b_1} (d*_{\text{int}} / t_{res}\sqrt{\alpha_n})^S} - \left[\frac{p_i D}{2t_{res}}\right] \tag{3.13}$$

If the linear internal corrosion model is used (Equation 3.7), resulting in an internal corrosion depth, $d*_{int}$, Equation 3.8 can be rewritten as:

$$t_{res} = t_p - (d*_{int}) = t_p - \{[C_0(1 - \frac{C_t}{C_0})\frac{D}{K}\frac{V}{L}]T\} \tag{3.14}$$

Substituting Equation 3.14 in Equation 3.13 yields:

$$G(X) = \{ \frac{\alpha \cdot K_q}{[a_1 \cdot (\frac{[C_0 \cdot (1-\frac{C_t}{C_0}) \cdot \frac{D}{K} \cdot \frac{V}{L}] \cdot T}{[t - C_0 \cdot (1-\frac{C_t}{C_0}) \cdot \frac{D}{K} \cdot \frac{V}{L} \cdot T]})^{b_1} \cdot (\sqrt{\alpha_n} \cdot [C_0 \cdot (1-\frac{C_t}{C_0}) \cdot \frac{D}{K} \cdot \frac{V}{L} \cdot T]/[t_p - C_0 \cdot (1-\frac{C_t}{C_0}) \cdot \frac{D}{K} \cdot \frac{V}{L} \cdot T])^S]} - \left[\frac{p_i \cdot D}{2 \cdot [t_p - C_0 \cdot (1-\frac{C_t}{C_0}) \cdot \frac{D}{K} \cdot \frac{V}{L} \cdot T]} \right] \} \tag{3.15}$$

For a given age of pipe or time of exposure, if *G(X)* is less than zero, then the pipe is considered to have failed and the probability of failure occurring is:

$$P(G) < 0 \tag{3.16}$$

In this analysis, the random variables are considered to be the water quality variables including the chlorine decay constant, *K*, and the ratio of chlorine concentration (Ct/C_0), the hydraulic characteristics including the water velocity, *V*, and water pressure, p_i, and the pipe physical characteristics including the pipe diameter, *D*, and pipe original thickness, t_p. MCS, FORM- and SORM-based approaches are applied to estimate the probability of failure using Equation 3.15. While MCS is the most accurate method, the FORM- and SORM-based approaches are applied in order to investigate the performance of these techniques for this problem i.e., to investigate the effect that the nonlinearity of the performance function has on estimates the probability of failure.

3.5 PROBABILITY OF FAILURE DUE T0 INTERNAL AND EXTERNALCORROSION

Sadiq et al. (2004) use probability analysis to estimate the reliability of the pipe in the face of external corrosion associated failure in cast iron water mains. They define the failure time as the time at which the total stresses exceed the pipe strength capacity.

The performance function relates all the variables of the stresses acting on the pipe, the pipe residual strength, and the external corrosion, and is defined as:

$$G(X) = \sigma_Y - \sigma_\theta \tag{3.17}$$

Substituting Equations 3.2 through 3.5 in Equation 3.1 for considering circumferential stresses, and Equations 3.1 and 3.10 in Equation 3.17 for estimating the performance function, yields:

$$G(X) = \frac{\alpha \cdot K_q}{a_1 \cdot (\frac{d*_{\text{int}+ext}}{t_{res}})^{b_1} \cdot (d*_{\text{int}+ext} / t_{res} \cdot \sqrt{\alpha_n})^S} - \left[\frac{p_i \cdot D}{2 \cdot t_{res}} + \frac{3 \cdot K_m \cdot I_c \cdot C_t \cdot F \cdot E_p \cdot t_{res} \cdot D}{A \cdot [E_p \cdot t_{res}{}^3 + 3 \cdot K_d \cdot p_i \cdot D^3]} + [1 + f_{frost}] \times \frac{3 \cdot K_m \cdot \gamma \cdot B_d^2 \cdot C_d \cdot E_p \cdot t_{res} \cdot D}{E_p \cdot t_{res}{}^3 + 3 \cdot K_d \cdot p_i \cdot D^3} \right] \quad (3.18)$$

If the Two-phase external corrosion (Equation 3.6) and linear internal corrosion model (Equation 3.7) are used, resulting in a corrosion pit depth, $d*_{ext} + d*_{\text{int}}$. Equation 3.8 may be rewritten as:

$$t_{res} = t_p - (d*_{ext} + d*_{int}) = \{t_p - ([aT + b(1 - e^{-cT})] + [C_0(1 - \frac{C_t}{C_0}) \frac{D}{K} \frac{V}{L} T])\} \quad (3.19)$$

Substituting Equations 3.19 in Equation 3.18 yields the general performance function *G(X)* which may be used to calculate the probability of failure due to the thinness of the pipe wall caused by both external and internal corrosion.

Often data required to define probability distribution functions (PDFs) are not available. Therefore, pre-defined distributions based on limited information are considered. Sadiq et al. (2004) identify some probability distributions for input variables for performing a risk analysis of external corrosion associated failures in water mains. These distributions, along with those used in a similar study of the probability of failure due to the thinness of the pipe wall caused by internal corrosion in Chapter 2, are used in this analysis.

The probability distribution functions for input variables related to all environmental and operational stresses, resistance capacity, and corrosion rates are used for evaluating probability of failure throughout the exposure time. The type of distributions, minimum and maximum value, and standard deviation for each input variable are provided in Table 3.1.

Table3.1 Probability distributions of input variables for calculating probability of failure

Variable	Symbol	Units	Type of distributions	Min.	Mean	Stdev.	Max.
Water pressure	p_i	MPa	Normal	0.1	0.45	0.12	0.8
Pipe diameter	D	mm	Normal	190	203.2	11.43	210
Wall thickness	t_p	mm	Normal		12	0.44	
Toughness corrosion coefficient	α		Uniform	10			13.5
Constants used for determining strength capacity	a_1		Uniform	0.3			0.5
	b_1		Normal	-0.3	-0.25	0.03	-0.2
Multiple of pit width	L		Uniform	3			5
Toughness exponent	S		Normal	0.5	1	0.1	1.2
chlorine decay constant	K	mg/l	Normal	$6.32*10^{-7}$	$1.01*10^{-6}$	$0.34*10^{-6}$	$1.36*10^{-6}$
Water velocity	V	m/s	Lognormal	0.6	1.8	0.5	2.7
Pipe length	A	mm	Normal		6100	200	
Ratio of chlorine concentration	C_t/C_0		Normal	0.5	0.94	0.04	1.3
Bending moment coefficient	Km		Lognormal		0.235	0.05	
Unit weight of soil	γ	N/mm^2	Normal		$18.85*10^{-6}$	$18.85*10^{-7}$	
Width of ditch	B_d	mm	Normal		500	114.3	
Calculation coefficient	C_d		Lognormal		1.32	0.2	
Modulus elasticity of the pipe	E_p	MPa	Normal		165000	33000	
Deflection coefficient	K_d		Lognormal		0.108	0.0216	
Final pitting rate constant	a	mm/yr.	Normal	0.001	0.009	0.009	0.015
Pitting depth scaling constant	b	mm	Normal	2.5	6.27	2	7.5
Corrosion rate inhibition factor	c	$yr.^{-1}$	Normal	0.01	0.1	0.05	0.18
Frost load multiplier	f_{frost}		Uniform	0			1
Impact factor	Ic		Normal		1.5	0.375	
Surface load coefficient	Cs		Lognormal		0.12	0.024	
Wheel load traffic	F	N	Normal	30000	41200	20000	100000

3.6 RESULTS AND DISCUSSION

The data in Figure 3.2 provide the results of the MCS, and the FORM- and SORM-based approaches for a 6.1 m, 203 mm diameter pipe, under the failure criteria for which the stress is due to water pressure exceeding the pipe strength capacity, and is only affected by internal corrosion. This pipe length and diameter were chosen by Sadiq et al. (2004) in their analysis and the same pipe type is selected herein in order to compare this work with their analysis. The nonlinearity of the performance function leads to a difference between the FORM and SORM results after approximately 40 years of exposure time. The likelihood of failure increases to nearly 50% in the 110th year of pipe age using MCS and the SORM-based approach. This indicates that the effect of internal corrosion on mechanical failure is lower, but on the same order of magnitude, as the effect of external corrosion on such failures. Sadiq et al. (2004) estimate a 50% likelihood of failure in the 70th year of pipe age in the case of external corrosion for the same type of pipe.

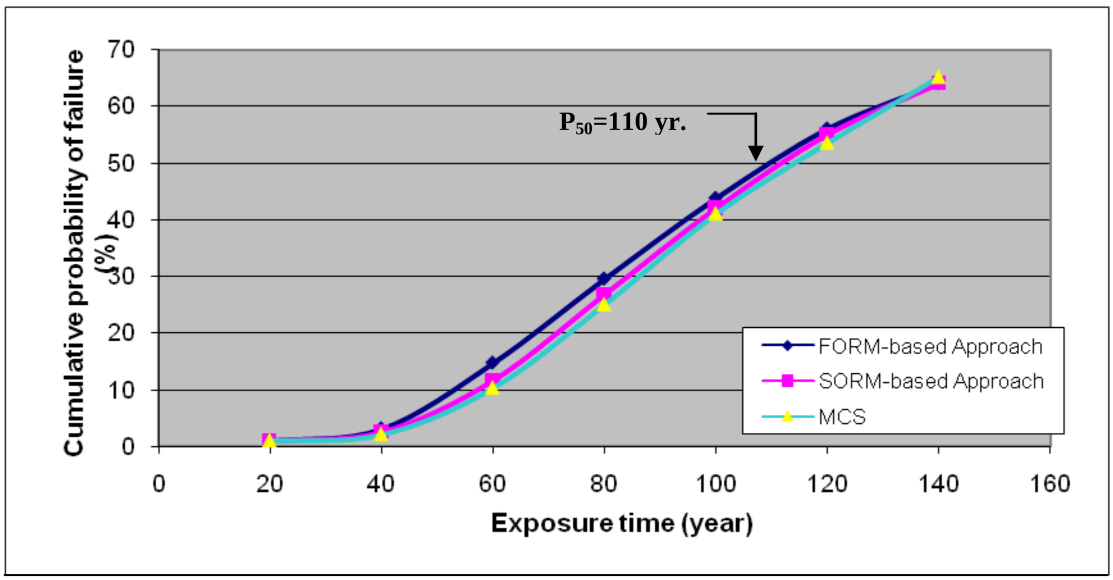

Figure3.2. Probability of failure due to the thinness of the pipe wall caused by internal corrosion throughout the exposure time using MCS, FORM- and SORM- based approaches (failure criteria of $\sigma_F \geq \sigma_Y$)

The data in Figure 3.3 provide the results of the MCS, and FORM- and SORM-based approaches for which the failure criteria is defined as the case in which the total stresses exceed the pipe strength capacity, affected by both external and internal corrosion. The likelihood of failure increases to nearly 50% in the 45th year of pipe age. While external corrosion has been shown to affect the pipe mechanical failure significantly and the effect of internal corrosion on mechanical failure is lower than that of external corrosion, the results show that the risk of mechanical failure may be further heightened if internal corrosion is considered.

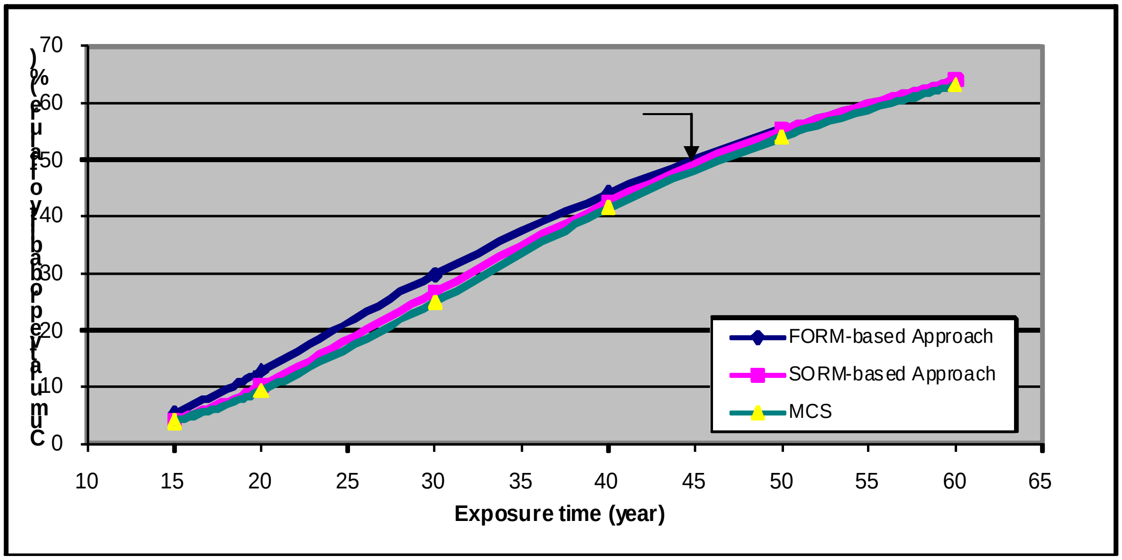

Figure 3.3. Probability of failure due to the thinness of the pipe wall caused by external and internal corrosion throughout the exposure time using MCS, and FORM- and SORM-based approaches (failure criteria of $\sigma_\theta \geq \sigma_Y$)

3.7 SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to identify the variables that have the most significant effect on the reliability index, β, and subsequently on the estimate of the probability of failure. The sensitivity of the reliability index to each of the water quality factors (C_t/C_0, K), hydraulic performance variables (V, p_i), and pipe structural characteristics related to its strength capacity is estimated and described in terms of sensitivity factors. The sensitivity factors provide the rate of change of the reliability index with respect to each of the random variables. These rates are given as the partial derivatives of β with respect to each of the variables. The sensitivity factors are determined using the Relan software, Version 7 (Foschi and Li 2005).

The results in Figure 3.4 indicate that the probability of failure due to only internal corrosion is most sensitive to the chlorine decay constant, K, the velocity of water, V, and the ratio of chlorine concentration, C_t/C_0, which represents the current concentration of chlorine as water travels through the pipe. These variables have the most influence on the probability of failure over the pipe life.

While the variable *K* has the most influence on the probability of failure prior to 105 years of pipe age, after this age the velocity becomes the most important variable throughout the life of the pipe. The correct measurement of *K* should be determined to reflect the appropriate internal corrosion rate in the pipe network. Therefore, advances in infrastructure asset management may benefit from further analysis of the chlorine decay constant to determine the accurate internal corrosion rate in the pipe network.

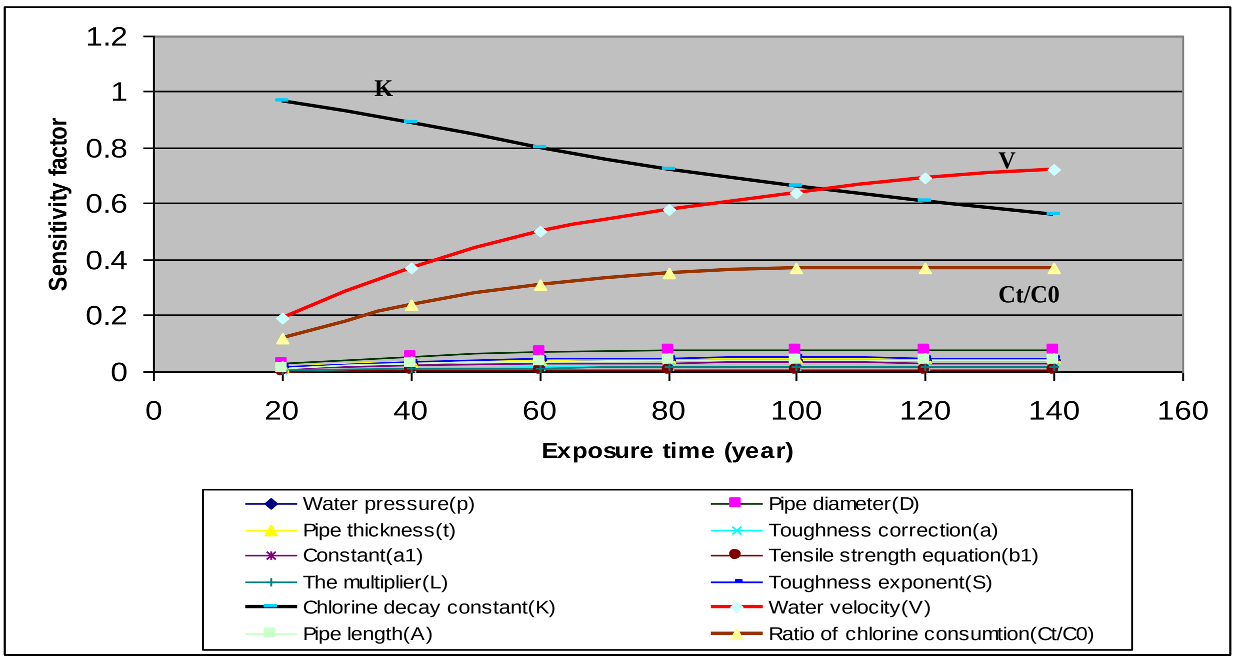

Figure 3.4. Sensitivity factors for input variables throughout the exposure time using a SORM-based approach (internal corrosion, failure criteria of $\sigma_F \geq \sigma_Y$)

The cost effective allocation of investments in these activities is time dependent, and will benefit from further analysis of how the chlorine decay coefficient changes as pipes age.

The ratio of chlorine concentration, Ct/C_0, is significant throughout the exposure time and is dependent on the initial chlorine concentration and the rate of corrosion. Thus, the analysis of chlorine boosting throughout a system, its influence on the rate of internal corrosion and on the chlorine concentration ratio is recommended as a means of further extending pipe life.

The results also show that the other variables in the performance function have a minimal effect throughout the pipe exposure time.

The data in Figure 3.5 provide the results of the sensitivity analysis of variables for predicting probability of failure due to the pipe wall thickness considering both external and internal corrosion. These results show that two of the variables of the internal corrosion model (K, Ct/C_0), and one of the variables of external corrosion model (the scaling constant for corrosion depth, b) are the most significant variables. Variable b has the maximum effect on the external corrosion and this implies that the future research should invest on the validation of the external corrosion model.

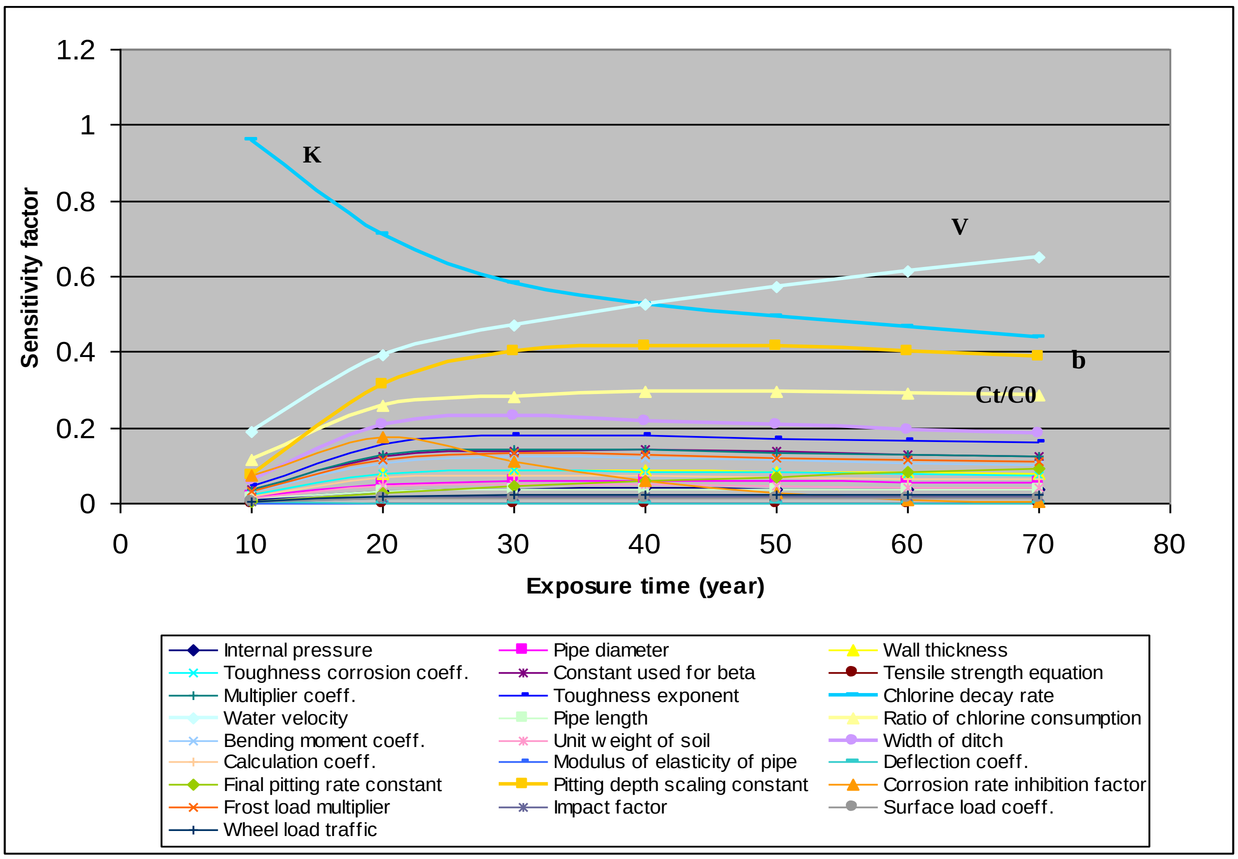

Figure3.5. Sensitivity factors for input variables throughout the exposure time using a SORM-based approach (external and internal corrosion, failure criteria of $\sigma_\theta \geq \sigma_Y$)

Another important variable is the water velocity which represents the hydraulic condition of the pipe segment. While the corrosion rate constant, *K*, has the most influence on the probability of failure prior to 40 years of pipe age, after that age the velocity becomes the most important variable throughout the life of the pipe. The value of K in early ages is higher because of the higher chlorine consumption and corrosion rate at these ages. In early ages, a rapid growth of the corrosion occurs because any corrosion products formed on the pipe surface are porous and have poor protective properties. After some years, a slow growth of the corrosion leading to a constant corrosion depth occurs due to the strong protective properties of the pipe.

3.8 SUMMARY AND CONCLUSIONS

The water quality variables, e.g., the ratio of chlorine concentration, can affect the pipe wall thickness caused by internal corrosion and thus contribute to the pipe mechanical failure. Considering the effect of internal corrosion on the pipe failure, a probabilistic analysis is used to estimate the probability of mechanical failure over exposure time.

The Two-phase external corrosion model is used in this chapter and is combined with the internal corrosion model developed in Chapter 2 to estimate the probability of overall mechanical failure of a pipe segment throughout the exposure time.

The probability of failure throughout the exposure time is estimated for two failure criteria using MCS, and FORM- and SORM-based approaches. The first criteria represents the pipe failure due to the thinness of the pipe wall caused by internal corrosion when the stress due to water pressure exceeds the pipe strength capacity and the second criteria represents pipe failure due to the thinness of the pipe wall caused by both internal and external corrosion when the total stresses exceed the pipe strength capacity.

The sensitivity factors are estimated to determine the variables that have the most influence on the reliability index and subsequently on the probability of failure throughout the exposure time. The contribution of chlorine residual, i.e., causing internal corrosion, soil properties, i.e., causing external corrosion, and hydraulic conditions to the estimates of the probability of failure are investigated. Compared with the all other variables in the environmental and other operational imposed stresses, the water quality factors in the internal corrosion model, e.g., the ratio of chlorine concentration, the scaling constant in external corrosion model, and the water velocity are the most important variables influencing on the probability of failure. This result points to a conclusion that the major effort should be invested in refining the internal and external corrosion models and their related variables.

The importance of the chlorine decay constant in modeling water quality has been extensively studied. The correct measurement of K should be determined to reflect the appropriate internal corrosion rate in the pipe network. Therefore, advances in infrastructure asset management may benefit from further analysis of the chlorine decay constant to determine the accurate internal corrosion rate in the pipe network.

The probability of mechanical failure due to the thinness of the pipe wall caused by external and internal corrosion may be used to obtain the likelihood of failure for a given residual pipe wall thickness and the number of pipe breaks for a given exposure time as surrogates for condition. This information may be useful in identifying the remaining service life and addressing the planning process for the rehabilitation and replacement of water mains in distribution systems.

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CHAPTER 4

Condition Assessment of Cast Iron Pipes in Water Distribution Systems

A version of this chapter has been submitted for publication. H. Yamini, B. J. Lence, and R. O. Foschi. Condition Assessment of Cast Iron Pipes in Water Distribution System.

PREFACE

Most water distribution systems in Canada and the USA are in poor condition and are deteriorating over time (Rajani and Mc Donald, 1995). Estimating the service life of the pipes and undertaking long term planning for their replacement depends on prediction of the future conditions of the water mains in the system. Estimates of the pipe condition provide utilities with a means of prioritizing pipe repair, and planning for rehabilitation, and replacement.

In cast iron pipes, the mechanical failure of a pipe due to internal and external corrosion is a function of the pipe wall thickness and thus probability of failure for a given residual pipe wall thickness may be considered as an indicator of pipe condition. In this chapter, the likelihood of failure for a given residual pipe wall thickness at a given pipe age is obtained and a modeling strategy inspired by survival analysis is used to estimate the number of pipe failures at that age. The annual number of pipe breaks and the likelihood of pipe failure for a given residual wall thickness throughout the exposure time are reasonable indicators of the structural state of the water mains in water distribution systems. This analysis relies on the probabilistic analysis of pipe failure due to internal and external corrosion conducted in Chapter 3 of the thesis.

Pelletier et al. (2003) estimate the hazard and survival functions for cast iron pipes with diameters of between 100 and 200 mm using pipe break data for the municipalities of Chicoutimi, Gatineau and Saint-Georges, Quebec. Pelletier (2000) and Mailhot et al. (2000) show that the best-fit function for the hazard function from installation to the first break is a Weibull distribution, and for all subsequent breaks is an Exponential distribution. Pelletier et al. (2003) also determine the survival functions for first breaks, based on their data.

In this work, the probability of failure estimates determined in Chapter 3 are used to estimate discrete probability density and hazard functions for specific pipe diameter (203 mm) and these discrete estimates are fit to a Weibull and Exponential distributions to estimate continuous forms of these functions. The survival function is then estimated based on these continuous functions. The estimated survival function compares well with those determined by Pelletier et al. (2003) based on data for cities having similar pipe sizes. An approach developed by Pelletier (2000) is then applied, along with the estimated continuous probability density, hazard, and survival functions, to estimate the number of pipe breaks that may be expected throughout the exposure time.

4.1. INTRODUCTION

It is well understood that cast iron water mains in North America are in poor condition and are deteriorating rapidly (Rajani and Mc Donald, 1995). These pipes are also the oldest pipes, and have a tendency to corrode externally and internally under aggressive environmental conditions.

Corrosion of pipes is a major factor in the weakening of pipe integrity and leads to several problems, including pipe breaks and loss of hydraulic capacity (Mays 2000). The resulting pipe breaks are also potential sources of contamination of the water distribution system. Water utilities are therefore facing the problem of managing deteriorating networks in the most efficient way possible to maintain existing and future levels of service.

In addition, further expansion of water distribution systems and the need for renewal of pipes increase financial stress on present budgets. Water utilities in Canada and in the USA invest capital and operating funds to maintain the water mains of distribution systems. Much of this expenditure is to repair or replace aging cast iron mains that have suffered from external and internal corrosion throughout the exposure time. It is estimated that the financial costs for pipe repair and replacement exceeds $1 billion annually in Canada alone (Rajani and Tesfamariam, 2005). Also, Selvakumar et al. (2002) report that the total costs of pipe repair and replacement exceeds $3.7 billion annually in the USA.

To meet predetermined levels of service for a deteriorating water distribution system, long-term planning is needed to prevent system failures and to repair or replace water mains just before a failure has occurred. The major objective of long-term planning is to maintain or improve the system reliability and operation regularity given a limited budget. The long-term planning of the renewal of water distribution systems requires the ability to predict system reliability and assess condition. The probability of failure for different pipe segments discussed in Chapters 2 and 3 estimates the potential of these pipes to break at different exposure times. In order to assess condition, general assessment of the structural behavior of pipes is needed, as are tools to estimate the pipe failure behavior. To make an assessment, data regarding the characteristics of pipes and their breakage histories must be collected. Unfortunately, many municipalities only have historical records for a decade, while their pipe ages are much greater. So, it may be difficult to trace the deterioration of the pipes over time. Also, field-based condition assessment is costly and only provides information for a pipe segment at a particular point in time. There is a need to improve the level of accuracy in pipe condition assessment that does not require a long history of data (De Silva et al. 2002).

This chapter develops an approach for assessing condition of water mains throughout the exposure time using the probability of failure due to internal and external corrosion and a modeling strategy inspired by survival analysis presented by Pelletier (2000) and Mailhot et al. (2000). The survival analysis is used to predict the failure behavior of water mains throughout the exposure time. The condition assessment approach may then be incorporated into plans of rehabilitation and replacement of pipes in water distribution systems.

In the following sections, the discrete probability density and hazard functions of pipe failures for a specific pipe diameter are estimated based on the probability analysis conducted in Chapter 3. Then the probability density and hazard functions are fit to Weibull and Exponential distributions to estimate continuous forms of these functions and the continuous survival function is determined based on these functions. The estimated survival functions are shown to compare well with those determined by Pelletier et al. (2003) for communities with pipes of a similar diameter. Next, probability density, hazard, and survival functions are used to determine the number of pipe failures throughout the exposure time. The likelihood of failure for a given residual pipe wall thickness is also estimated as a surrogate for pipe condition using a probabilistic analysis. The number of pipe failures and likelihood of failure for a given residual pipe wall thickness may then be considered as indicators of the structural condition of water mains.

4.2. ESTIMATING THE NUMBER OF PIPE FAILURES DUE TO CORROSION

4.2.1 Estimates of the cumulative probability of failure due to corrosion

The cumulative probability of failure as a function of exposure time is evaluated based on the results of the analysis conducted in Chapter 3. When total environmental, e.g., due to soil, traffic, and frost, and operational, e.g., due to water pressure, stresses approach the pipe strength capacity, the chance of pipe breakage is increased and the overall reliability of a pipe segment is reduced. Modeling stresses and internal and external corrosion acting on a pipe segment involves uncertainties in the model and its input parameters. The high degree of uncertainty associated with the parameters that affect pipe failures warrants a probabilistic-based analytical approach.

The concentration of chlorine residual, as one of the water quality parameters, can influence the internal corrosion rate and contribute to pipe mechanical failure. Considering the effect of internal corrosion on the pipe failure, a probabilistic analysis is used to estimate the probability of mechanical failure throughout the exposure time in Chapter 2. The Two-phase external corrosion model (Rajani et al. 2000) is then combined with the internal corrosion model to estimate the probability of overall mechanical failure of a pipe segment throughout the exposure time in Chapter 3. The failure criterion is defined as the time at which the stress due to environmental and operational stresses exceeds the pipe strength capacity. The results indicate that the likelihood of failure of a cast iron pipe due to internal and external corrosion is nearly 50% by the 45th year of exposure. Figure 4.1 shows the cumulative probability distribution throughout the exposure time using a SORM-based approach. All probability estimates are determined using the Relan software, Version 7 (Foschi and Li 2005).

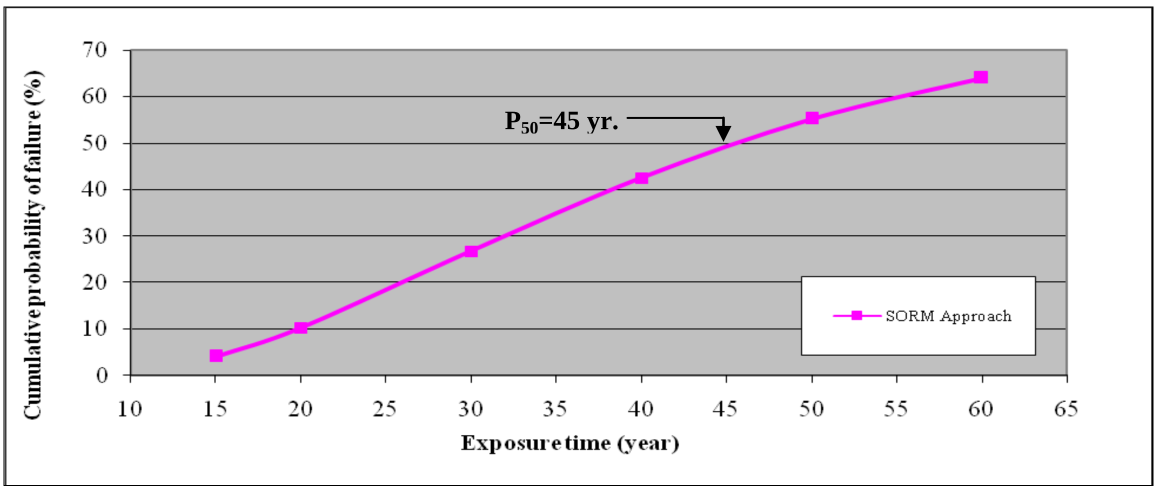


Figure 4.1. Probability of failure due to external and internal corrosion throughout the exposure time, for various statistical distributions using SORM-based approach (203 mm pipe diameter)

The data in Figure 4.1 and a modeling approach inspired by survival analysis conducted by Pelletier (2000) and Mailhot et al. (2000) are used in this work to determine the number of pipe failures throughout the exposure time. Pelletier et al. (2003) estimate the hazard and survival functions for cast iron pipes with diameters of between 100 and 200 mm using a limited history of pipe break data for the Quebec communities of Chicoutimi, Gatineau and Saint-Georges. Pelletier (2000) and Mailhot et al. (2000) show that the best-fit function for the hazard function from installation to the first break is a Weibull distribution, and for all subsequent breaks, is an Exponential distribution. Pelletier et al. (2003) also determine the survival function for first breaks, based on their data. The cumulative probability of failure data in Figure 4.1 are used herein to estimate probability density and hazard functions and thus the survival functions. Pelletier (2000) develops an approach for estimating the number of pipe breaks throughout the exposure time that integrate the probability density, hazard, and survival functions and this approach is used herein for estimating this indicator of the condition of a pipe segment.

4.2.2 Estimates of the number of pipe failures

The probability distribution function, *f (T)*, may be estimated by evaluating the continuous or discrete derivative of the cumulative probability function of pipe failure with respect to time. In this chapter, the discrete values of the probability distribution function are estimated by evaluating the derivative of the cumulative probability function shown in Figure 4.1, where the derivative is the ratio of the difference between the discrete values of the cumulative probability of failure at times T_1 and T_2 and the difference between discrete values of T_1 and T_2. The discreet value of probability distribution function is defined as Equation 4.1.

$$f(T_2) = \frac{F(T_2) - F(T_1)}{T_2 - T_1} \tag{4.1}$$

The hazard function, or instantaneous failure rate, λ *(T)*, is the probability that a pipe experiences a failure between time T_1 and T_2 given that the pipe segment is operating at time zero and has survived to time T_1 (Kapur and Lamberson 1977). The discrete hazard function may be determined by evaluating Equation 4.2 which relates the hazard function, the probability distribution function and the cumulative probability function, *F (T)*, of pipe failure at discrete points.

$$\lambda(T) = \frac{f(T)}{1 - F(T)} \tag{4.2}$$

Pelletier (2000) and Mailhot et al. (2000) determine that the Weibull distribution best describes the period of time to failure from pipe installation to the first pipe break, called the first break order, and that the Exponential distribution best describes the period of time to subsequent breaks, i.e., time to failure from the first to second pipe break, the second to the third, etc. The Weibull and Exponential distributions are provided in Equations 4.3 and 4.4, respectively:

$$\lambda(T) = kp(kT)^{p-1} \tag{4.3}$$

$$\lambda(T) = k_2 \tag{4.4}$$

The Weibull distribution is defined by two parameters, *k* and *p* and the Exponential distribution is a special case of the Weibull distribution where *p=1*, with only one parameter, k_2.

Data in Figure 4.2 show the discrete probability distribution function of pipe failure based on the cumulative probability function of pipe failure determined in Chapter 3 and the best-fit Weibull distribution for these data. Data in Figure 4.3 also show the discrete hazard function for the first order breaks, based on Equation 4.2 and the discrete probability distribution function, as well as the best-fit Weibull distribution for these data.

The parameters of the Weibull distribution, *k* and *p*, are 1.552 and 0.017, respectively. The estimate of *p*, being greater than one, corresponds to the case where the risk of pipe failure is low at early pipe ages and increases over the exposure time. The Exponential distribution that describes the hazard function for all subsequent breaks is also fit to these data, resulting in an estimate of k_2 of 0.011.

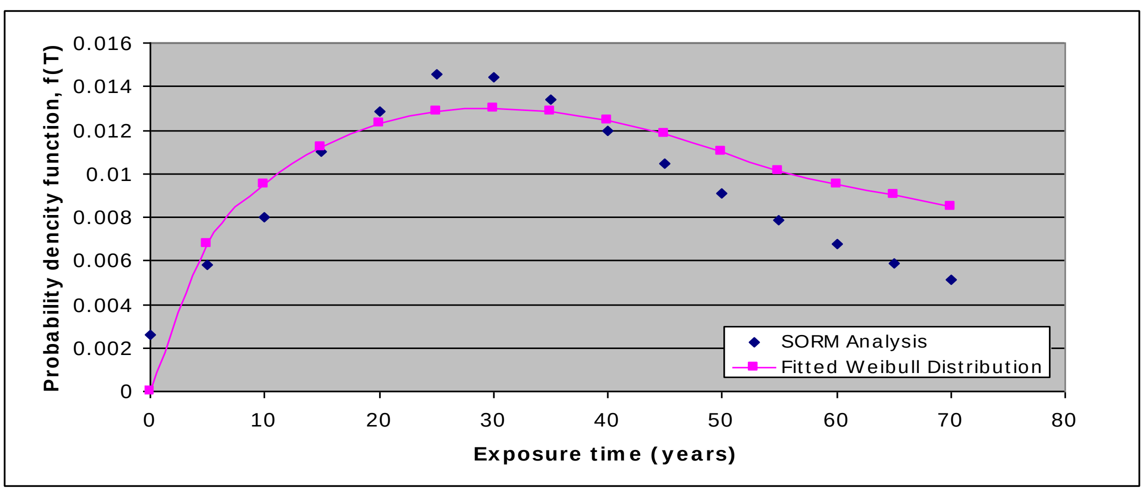


Figure 4.2. Discrete probability density function fit to the Two-parameter Weibull distribution function (*p*=1.552, *k*=0.017)

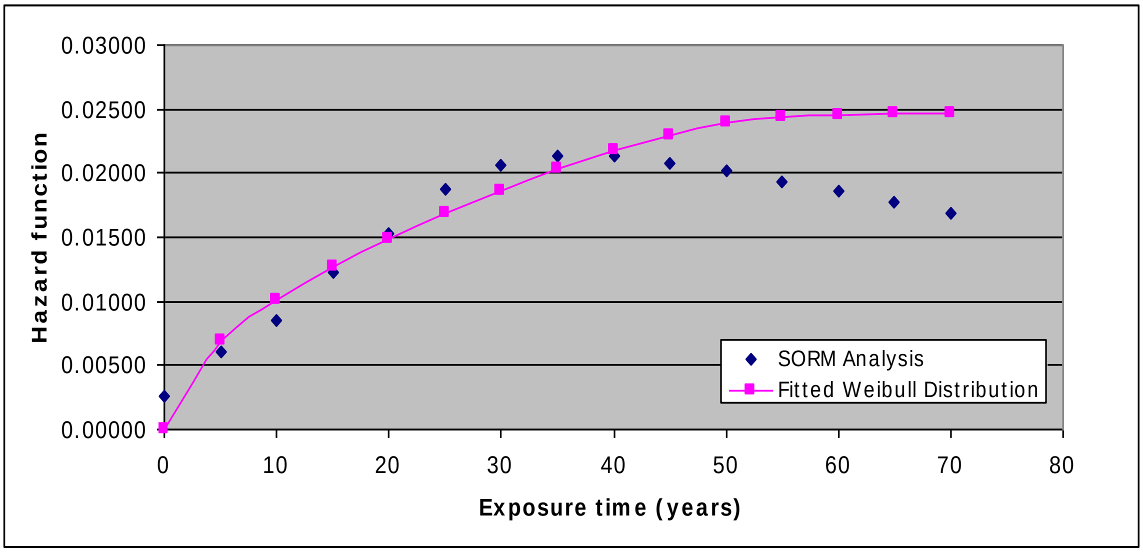


Figure 4.3. Discrete hazard function fit to the Two-parameter Weibull distribution function (p=1.552, k=0.017)

Pelletier (2000) estimates the number of pipe breaks at a given time, based on continuous estimates of the probability density, hazard and survival functions for the data published in Pelletier et al. (2003). Assuming that the reference time $T=0$ corresponds to the year of pipe installation, the number of pipe breaks for a given pipe segment between time T_1, and T_2, $\bar{n}(T_1, T_2)$, are estimated as:

$$\bar{n}(T_1,T_2) = [S(T_1) - S(T_2)] + k_2\{T_2[1 - S(T_2)] - T_1[1 - S(T_1)] - \int_{T_1}^{T_2} dt \times t \times f_1(T)\} \quad (4.5)$$

The survival function is the complement of the cumulative probability of failure, and is an estimate of the likelihood of a pipe surviving at a given exposure times T_1 and T_2. Kalbfleisch and Prentice (1980) define the survival function, and show that it may be represented by a Weibull distribution at time T, as:

$$S(T) = \exp[-(kT)^p] \quad (4.6)$$

For the estimate of the continuous hazard function for the first order breaks shown in Figure 4.3, the resulting survival function is shown in Figure 4.4. The estimated number of breaks, for an assumed length of pipe of 1000 m, can then be determined based on the estimated probability density and survival functions and these are provided in Figure 4.5.

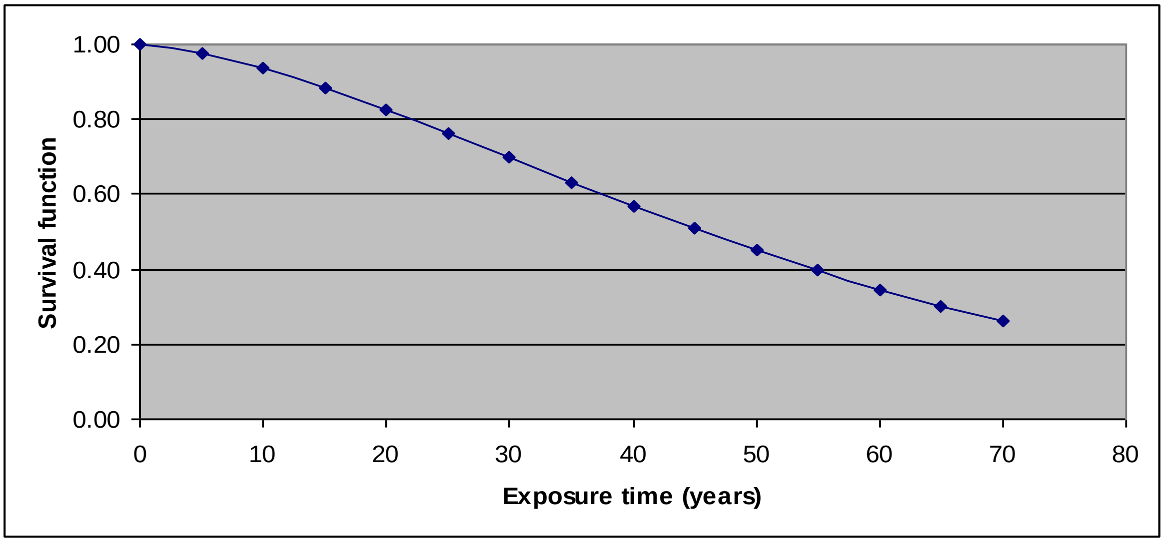


Figure 4.4 Survival function based on the hazard function for first order breaks

In this analysis, the input parameters associated with environmental and operational loads and the structural integrity of the pipe due to external and internal corrosion are taken into account in estimating the average number of pipe failures. The factors contributing to the number of pipe breaks over exposure time are comprised of water quality considerations, e.g., the ratio of chlorine concentration, hydraulic performance, e.g., water velocity and internal water pressure, external stresses, e.g., stress due to soil pressure, traffic and frost loads, and the rate of internal and external corrosion.

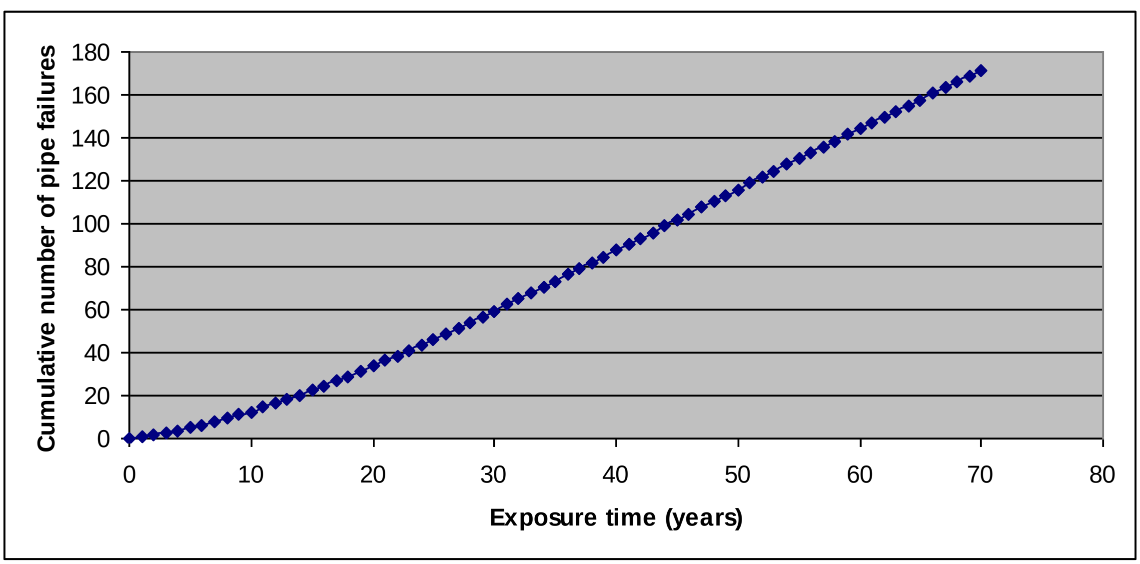


Figure 4.5. Cumulative number of pipe failures based on the results of SORM-based approach fitted to the Weibull and Exponential distributions

4.3 ESTIMATES THE LIKELIHOOD OF FAILURE FOR A GIVEN RESIDUAL PIPE WALL THICKNESS

The probability of mechanical failure of a pipe segment at a given pipe age is related to its relative residual pipe wall thickness, t_{res}, based on the following load- resistance equation, which is based on the modification of work conducted by Rajani et al. (2000), and developed in Chapter 3. The performance function, *G(X)*, is determined based on the assumption that failure occurs when the total environmental, e.g., due to soil, traffic, and frost, and operational, e.g., due to water pressure, stresses surpass the pipe strength capacity. It is defined as:

$$G(X) = \frac{\alpha \cdot K_q}{\beta \cdot (d*_{\text{int}+ext} / t_{res}\sqrt{\alpha_n})^S} - \left[\frac{p_i D}{2t_{res}} + \frac{3 \cdot K_m \cdot I_c \cdot C_s \cdot F \cdot E_p \cdot t_{res} \cdot D}{A \cdot [E_p \cdot t_{res}{}^3 + 3 \cdot K_d \cdot p_i \cdot D^3]} + [1 + f_{frost}] \times \frac{3 \cdot K_m \cdot \gamma \cdot B_d^2 \cdot C_d \cdot E_p \cdot t_{res} \cdot D}{E_p \cdot t_{res}{}^3 + 3 \cdot K_d \cdot p_i \cdot D^3} \right] \quad (4.7)$$

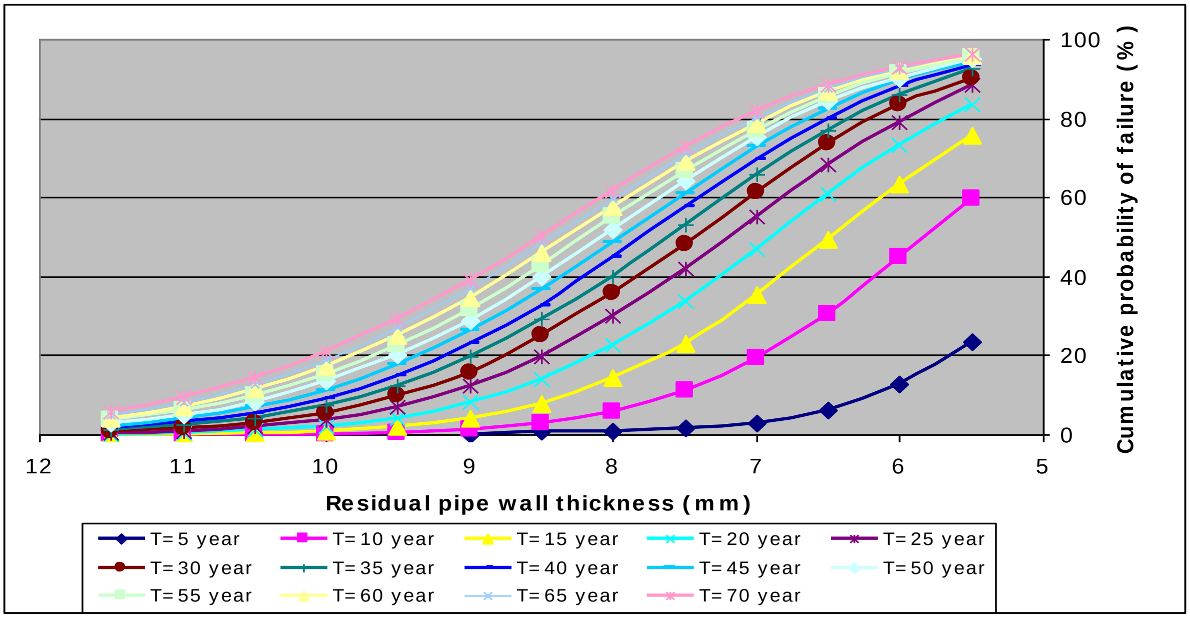
Where

$$t_{res} = t_p - (d*_{ext} + d*_{\text{int}}) = t_p - \{aT + b(1 - e^{-cT}) + [(1 - \frac{C_t}{C_0})\frac{D}{K}\frac{V}{L}]T\} \quad (4.8)$$

For a given age of pipe or time of exposure, if *G(X)* is less than zero, then the pipe is considered to have failed and the probability of failure occurring is:

$$P(G) < 0 \quad (4.9)$$

The cumulative probability of failure, for a 6.1 m length of 203 mm diameter with an initial pipe wall thickness of 12 mm, is estimated for a given residual pipe wall thickness and a given pipe age, and these data are shown in Figure 4.6. This analysis may be applied for different pipe diameters to determine how the likelihood of failure for a given residual pipe wall thickness varies with pipe age and pipe diameter.



Figures 4.6. Cumulative probability of failure vs. residual pipe wall thickness, for a SORM-based approach, for different exposure times (pipe ages)

4.4 RESULTS AND DISCUSSION

The data in Figure 4.3 show the estimated discrete hazard function given the results of the SORM-based analysis for a specific pipe diameter. These results indicate that the discrete hazard function declines after the first 40 years of pipe age. Given that the frequency of breakage of aging pipes is increasing (Sadiq et al. 2004), one might expect the failure rate, or hazard function, to increase due to the pipe deterioration throughout the pipe exposure. Two important assumptions made in this study may have contributed to the decreasing failure rate observed. The first assumption is that the internal and external corrosion is considered to be a self-inhibiting process whereby the protective properties of corrosion products reduce the corrosion rate over time (Ahammed and Melchers 1994; Snoeyink and Wagner 1996), and then stabilize at a constant rate thereafter. If this were not the case, the corrosion rate may have continued to increase with time, thereby increasing the failure rate. The second assumption is that the focus of the external corrosion analysis is on a single corrosion pit. If on the other hand, the probability of failure was determined based on an assumption that many external corrosion pits were being generated over the length of the pipe segment as it ages, Sadiq et al. (2004) observes that the probability of pipe failure would increase, causing an increase of the failure. In this study, the probability of failure analysis deals solely with the contribution of a single external corrosion pit. More research is needed to analyze the formation of corrosion pits over the length of the pipe segment and thus to define the estimate of failure frequency observed in aging water mains.

The data in Figure 4.4 show the continuous survival function at different pipe ages estimated based on the Wiebull distribution, i.e., based on the hazard function that reflects the time to failure from installation to first break. The survival function represents the likelihood of a pipe surviving to a given exposure time *T*. The higher the curve, the longer it takes for the first failure to occur. These data show that at about 10 years after installation, the pipe segment has not failed.

Data in Figure 4.5 show the estimated cumulative number of pipe failures per 1000 m of cast iron pipe. The results show that the number of failures increases throughout the exposure time. For example, after 45 years of pipe installation, the cumulative number of pipe breaks is about 100. This may be considered as a diagnostic tool for condition assessment because asset managers are facing problems associated with determining how and what to evaluate, defining what constitutes condition and indices, and determining how to use data related to the condition of the assets. The number of pipe failures may also be estimated for pipes of different diameters.

Data in Figures 4.6 show the cumulative probability of failure for a given residual pipe wall thickness for different exposure times, i.e., pipe ages. This may be considered as a second indicator of pipe condition. For example, for a pipe segment with a 12mm original wall thickness that is 45 years old, the likelihood of failure is about 50% when the residual pipe wall thickness is 7.8mm.

4.5 TOWARD ASSESSING PIPE CONDITION AND REPLACEMENT STRATEGIES

The goal of infrastructure management is to minimize life-cycle rehabilitation costs for an infrastructure system while meeting an acceptable performance level. Therefore, an economic analysis is essential for determining an optimum replacement time for water mains that are failing mostly due to corrosion, and the budgetary needs for future repairs under various replacement and rehabilitation strategies.

To undertake an economic analysis, the following input data are required: 1) the projected number of pipe failures throughout the exposure time; 2) the cost of repairing one break or failure; and 3) the discount rate used in converting future expenditures to present value (Shamir and Howard 1972). If these input data are known, utility managers may evaluate: 1) the present value (dollars) of all future repairs for the existing pipe as a function of the pipe age; 2) the present value (dollars) of replacing the existing pipe with a new pipe as a function of the pipe age; and 3) the total life-cycle cost as a function of pipe age, which is the sum of the present values of all future pipe repairs and replacements. The optimal year for pipe replacement is equal to the year at which the total life-cycle cost is a minimum.

The probability of failure for a given residual pipe wall thickness and age may be used as a complementary condition indicator to assess the service life of a pipe segment. Depending on discount rates, and costs of repairing a pipe, it may be more or less conservative than the results of an economic analysis of the optimal year of pipe replacement. For example, assume that a utility manager would only accept a likelihood of failure of 50% for any age of pipe. For a 6.1 m long pipe with a 203 mm diameter, and an original pipe wall thickness of 12 mm, at the 45th year of pipe age, and a residual pipe wall thickness of 7.8 mm, the likelihood of failure is 50% (see Figure 4.6). Therefore if a given pipe has a wall thickness of less than or equal to 7.8 mm at this pipe age, the utility may choose to repair the pipe. If, on the other hand, based on an economic analysis which includes an estimate of the number of pipe failures (see Section 4.2), the optimal year of pipe replacement is year 50, the utility manager may have waited to replace the pipe at its 50th year.

4.6 MODEL VALIDATION

A survey of over 200 municipalities in the Province of Quebec reveals that few municipalities have maintained computerized records of pipe breaks for longer than a decade (Fougeres et al. 1998). Pelletier et al. (2003) fit these data to Weibull, i.e., time to failure from installation to first break, and Exponential distributions, i.e., time to failure from the first to second pipe break, the second to the third, etc, for determining the survival function and predicted behavior of pipe breaks throughout the exposure time. The survival function based on the Weibull distribution is presented for the three municipalities, where A corresponds to the City of Chicoutimi, B to Gatineau, and C to Saint-Georges, is shown in Figure 4.7. Preliminary analyses conducted by Pelletier et al., (2003) with data from Chicoutimi and Gatineau show that pipe segments installed after 1960 have a different pipe failure behavior than those installed before 1960. Therefore, two sets of parameters are estimated for the two municipalities. A1 and B1 represent all pipes installed before 1960, and A2 and B2 represent those installed after 1960, for Chicoutimi and Gatineau, respectively. The reason for this behavior is not well understood, but it may be related to the pipe installation technique, variation in soil characteristics, and water quality in the pipe over time.

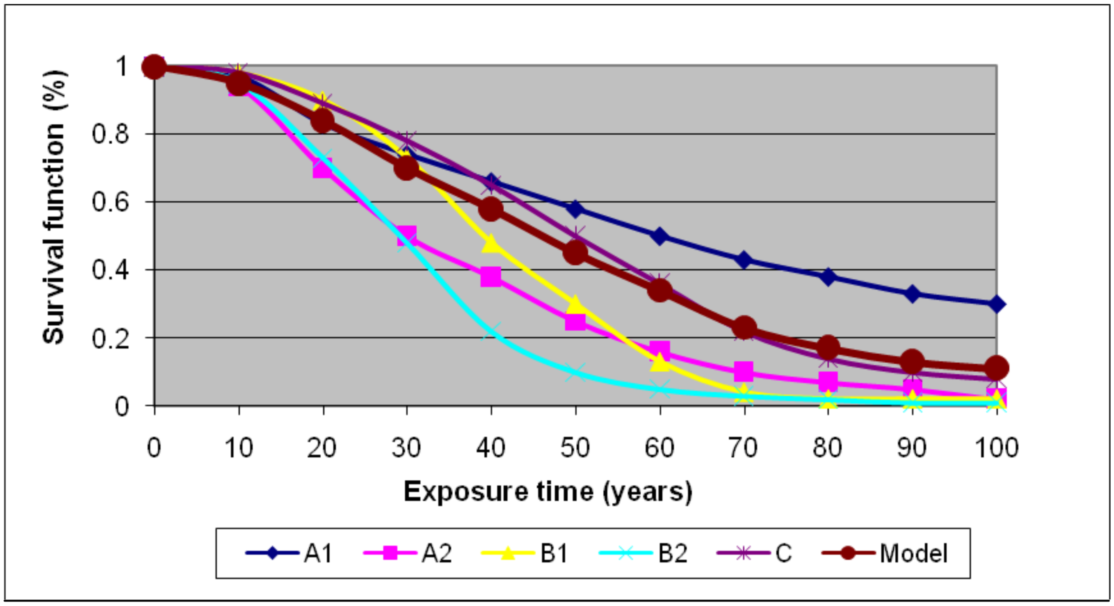


Figure 4.7. Comparing the survival functions for three municipalities with survival function associated with the Weibull Distribution using the SORM-based approach

Data in Figure 4.7 indicate that pipe segments for B2 and A2 groups are at the highest risk for subsequent failures while pipe segments in group C face a moderate, and those in group A1 face the lowest risk. The results show that the continuous survival function associated with the SORM-based analysis (model) developed in Chapter 3 and estimated based on the Weibull distribution lies within the survival functions for three municipalities with different historical records of pipe breaks. Figure 4.7 also shows that the survival function derived from this work has nearly the same behavior of the data related to the City of Saint-Georges (C), which has the moderate risk of subsequent failures.

4.7 CONCLUSIONS

This chapter develops an approach that incorporates the probability of mechanical failure with an appropriate probability-based predictive pipe breakage model, i.e., survival analysis, to obtain the condition of water mains in a predefined planning period. The probability of mechanical failure due to external and internal corrosion and the predictive pipe breakage model are used to estimate the number of pipe breaks and the likelihood of failure for the residual pipe wall thickness for a given exposure time as surrogates for condition.

Estimated probability density and hazard functions based on the probability analysis are fit to the Two-parameter Weibull and Exponential distributions. The parameters of these distributions are then incorporated in a modeling strategy inspired by survival analysis, conducted by Pelletier (2000) and Mailhot et al. (2000), to determine the number of pipe failure throughout the exposure time. The results show that after 45 years of pipe installation, the cumulative number of pipe breaks is about 100 for a 1000 m of pipe segment of cast iron pipe.

In this chapter, the likelihood of failure for a given residual pipe wall thickness is considered as the second condition indices in water distribution systems. The likelihood of failure for a given residual pipe wall thickness may be estimated for any given time of pipe exposure. The likelihood of failure for a given residual pipe wall thickness at a given pipe age and the number of predicted breaks using survival analysis can serve as surrogate for condition in developing a comprehensive replacement strategy and can be coupled with economic assessment models in the analysis of future asset management decisions.

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CHAPTER 5

CONCLUSIONS

5.1 SUMMARY

The major contributions of this thesis are:

A methodology for estimating the probability of mechanical failure of cast iron pipes due to internal corrosion

Most water utility engineers are familiar with the typical failure modes of cast iron pipes such as circumferential and longitudinal breaks. However, while researchers have examined the effects of external corrosion that are likely responsible for these failures, the effects of internal corrosion have not been thoroughly investigated. Therefore, the effect of internal corrosion is considered in this research to determine a comprehensive methodology for calculating pipe mechanical failure.

1. How may the probability of mechanical failure due to internal corrosion during the exposure time be determined?

In Chapter 2, the prime focus is the estimation and analysis of the probability of failure in cast iron pipes due to the thinness of the pipe wall caused by internal corrosion. Considering water quality parameters, i.e., the chlorine concentration ratio, C_t /C_0, and hydraulic conditions, i.e., the water velocity, V, affect the internal corrosion rate and their contribution to pipe mechanical failure, a probabilistic analysis is used to estimate the probability of mechanical failure throughout the exposure time. MCS, FORM-, and SORM-based approaches are used to perform the probabilistic analysis.

2. What corrosion factors significantly affect the failure probability due to internal corrosion?

The result of the sensitivity analysis in Chapter 2, Section 2.6, indicates that the probability of mechanical failure due to internal corrosion is more sensitive to water quality parameters than to hydraulic conditions. The results show that the chlorine concentration ratio and chlorine decay constant have the highest influences on the probability of mechanical failure due to internal corrosion. The ratio of the chlorine concentration represents the current concentration of chlorine as water travels through the pipe and the chlorine decay constant represents the importance of corrosion rate accuracy for a pipe segment. These parameters are dependent on the initial chlorine concentration and the rate of internal corrosion.

3. How may uncertainties in corrosion factors contribute to mechanical pipe failures due to internal corrosion?

In cast iron pipes, chlorine decay due to internal corrosion is high compared with consumption caused by other water quality parameters in such systems (Kiene et al. 1998), and is considered in this work as an approximate indicator of the rate of internal corrosion that leads to the loss of pipe wall thickness and pipe mechanical failure. Rajani et al. (2000) also show that the effect of internal fluid pressure is significant compared with environmental pressures for determining circumferential stress. In this thesis, the chlorine concentration ratio, C_t/C_0, chlorine decay constant, K, water velocity, V, and water pressure, p_i, are the major uncertain parameters or conditions used in the performance function to estimate the pipe mechanical failure due to internal corrosion.

Two failure modes are defined as: 1) the point at which the internal corrosion depth is more than the maximum acceptable decrease in pipe wall thickness, d_p, set by the utility manager (Chapter 2, Section 2.4), and 2) the point at which the stress due to water pressure exceeds the pipe strength capacity under the assumption that no environmental pressures affect the pipe failure throughout the exposure time (Chapter 3, Section 3.4). The original pipe thickness, t_p, is replaced with residual pipe thickness, t_{res}, which is a function of water quality parameters, i.e., chlorine concentration ratio, and hydraulic conditions, i.e., water velocity.

A methodology for estimating the probability of mechanical failure of cast iron pipes due to internal and external corrosion

4. How can the probability of mechanical failure due to internal and external corrosion during the exposure time be determined?

The environmental and operational loads that lead to pipe mechanical failure due to external corrosion are reviewed in Chapter 1. The Two-phase external corrosion model (Rajani et al. 2000) is combined with the internal corrosion model developed in Chapter 2, Section 2.4, to estimate the probability of overall mechanical failure of a pipe segment throughout the exposure time. In Chapter 3, Section 3.5, MCS, and FORM- and SORM-based approaches are used to calculate the overall probability of mechanical failure throughout the exposure time.

In this research, the performance function is developed that defines mechanical pipe failure in terms of the reduction in the pipe wall thickness caused by both internal and external corrosion. Here a pipe failure occurs when the total environmental and operational stresses, e.g., stresses due to internal water, soil, traffic, and frost pressures exceed the pipe strength capacity. Using this failure definition allows for a comparison to be made with the failure definition for the probability of failure due to only external corrosion estimated by Sadiq et al. (2004).

The result of the sensitivity analysis in Chapter 3, Section 3.7, indicates that the water quality parameters, i.e., chlorine concentration ratio, chlorine decay constant, hydraulic performance, i.e., water velocity, and one of the parameters of the Two-phase external corrosion model, i.e., the pitting depth scaling constant, *b*, have the highest influence on the time to failure.

A methodology for assessing the condition of the pipe segment

5. How may one estimate the predicted annual number of failures of cast iron pipes due to internal and external corrosion?

Pelletier et al. (2003) estimate the hazard and survival functions for cast iron pipes with diameters of between 100 and 200 mm using pipe break data for the three municipalities in Quebec. Pelletier (2000) and Mailhot et al. (2000) show that the best-fit function for the hazard function from installation to the first break is a Weibull distribution, and for all subsequent breaks, is an Exponential distribution. Pelletier et al. (2003) also determine the survival function for first breaks, based on their data.

In this research, the probability of failure throughout the exposure time, determined in Chapter 3, is used to estimate discrete probability density and hazard functions. The discrete estimates of the probability density and hazard function are fit to the Weibull and Exponential distributions to estimate the continuous forms of these functions. An approach developed by Pelletier (2000) is then applied to estimate the number of pipe breaks that may be expected throughout the exposure time using the estimated continuous probability density, hazard, and survival functions. The predicted number of pipe breaks over time is used as one condition indicator to assist in developing future planning strategies.

6. How may one use the information from this research for assisting in condition assessment and long-term planning for replacement of water mains in a distribution system?

The number of pipe breaks over the exposure time and the likelihood of failure for a given residual pipe wall thickness are considered as condition assessment indicators. The economic analysis is needed to estimate the optimal time of pipe replacement. Estimating optimal time of pipe replacement requires the information related to the projected number of pipe failures throughout the exposure time, cost of repairing pipe break, and discount rate used in converting future expenditures to present value (Shamir and Howard 1972). The probability of failure for a given pipe wall thickness and age may be used as a complementary condition indicator to assess the service life of a pipe segment. Depending on discount rates, and costs of repairing a pipe, it may be more or less conservative than the results of an economic analysis of the optimal year of pipe replacement.

5.2 LIMITATIONS

The methodology developed herein that uses a probabilistic risk analysis of both internal and external associated failures has the several limitations. The corrosion reaction is limited by the production rate of ferrous iron, Fe^{2+}, and the chlorine residual traveling through the pipe is the only oxidant of ferrous iron, i.e., *HOCl* is the main oxidant. A linear relationship between the rate of internal corrosion and the corrosion depth (based on observations made by Snoeyink and Wagner, 1996) is assumed. The results of the analysis would have varied significantly if a nonlinear internal corrosion rate was assumed. The loss of pipe wall due to the internal corrosion process around the pipe is also assumed to be uniform. The results of the analysis also would have varied if a localized corrosion pit was assumed.

The distribution of all input variables, i.e., parameters associated with environmental and operational loads in the internal and external corrosion models, are assumed to be independent, i.e., it is assumed that there is no correlation between parameters, for estimating the probability of pipe failure. The correlation between variables may have an effect on the results of probability of failure analysis. When the variables are considered to be correlated, the random variables that are partially or highly correlated may counter-balance each other and cause only a moderate variation in probability of failure at a given exposure time.

Internal, e.g., internal fluid pressure, and external, e.g., soil pressure, loads may cause stress in both the circumferential and longitudinal directions. In this research, the effect of the loads in the circumferential direction is considered under the assumption that the pipe is uniformly loaded and supported along its length to estimate the overall probability of pipe failure (Ahammed and Melchers 1994). Therefore, the effect of pressure gradients, σ_T , due to temperature differences along the pipe on the longitudinal stress and thus on the estimate of the probability failure is also neglected as it is one of the parameters for estimating the longitudinal stress. The variation in the probability of failure might be significant if the quality of pipe installation is poor or the pipe is not uniformly loaded along its length.

The discrete hazard function in Chapter 4, Figure 4.3, declines after the 40th years of pipe age. One might expect that as the pipe ages its failure rate should increase due to deterioration. Two important assumptions made in this study may have contributed to the decreasing failure rate observed. First, assuming the internal corrosion rate as a self-inhibiting process whereby the protective properties of corrosion products reduce the corrosion rate over time and then stabilize at a constant rate thereafter. Second, a single external corrosion pit is considered in the probability of failure analysis. If these were not the case, the corrosion rate may have continued to increase with time, thereby increasing the failure rate. More research is needed to explain more about the hazard function (or failure rate) behavior.

In general, water quality failure, sloughing effects, and bending stress due to soil movement and pipe installation quality has not been modeled due to the varied, uncertain, and complex parameters involved in installation. The results of the analysis also would have varied significantly if these are considered in the model. Some of these limitations should be improved and the assumptions explained in future research.

5.3 APPLICABILITY TO PRACTICE

5.3.1 Time-variant variables

This research is based on a time-invariant analysis with the assumption that all of the variables are time-independent (not a function of time) in estimating the probability of failure of a pipe segment due to corrosion. A time-variant risk analysis incorporates random variables that are time-dependant. Thus the general performance function and resulting failure analysis would also be time-dependant. In this type of analysis the random variables and subsequently the performance function should be characterized by a stochastic process.

In this study, the consumption of chlorine traveling through the pipe is assumed as a stationary process as travel time is defined as the ratio of the length of the pipe and the velocity, and this is used to account for the hydraulic conditions of the system. Also, the environmental and operational loads such as traffic loads or water pressure are considered to be time independent, as well as the chlorine dosage provided at the head of the pipe. However, in reality, these variables are generally a function of time and may be characterized by stochastic processes. Any time-variant reliability problem requires a stochastic process model for the random variables, such as a time-series model. Otherwise the problem cannot be properly analyzed.

In addition, the statistical information such as the mean value of random variable for each time step (for a time-series model) must be known. In the case of environmental loads, this requires a complex model to represent a relationship between environmental loads and time, which are not well documented currently. To account for the variation of chlorine in the system, an appropriate stochastic process must also be defined. Data related to the statistical information (e.g., mean value for the ratio of chlorine concentration) for each time step must be known or estimated. A time-dependent reliability analysis to account for the variation of random variables with time is reserved for future research. The variation in the probability of failure may be significant if the time-variant analysis were used assuming that all the time-dependent functions could be estimated.

5.3.2 The effects of water quality parameters on the probability of failure

In this research, the chlorine decay-corrosion rate model (Kiene et al. 1996) is used to develop the internal corrosion model for estimating the probability of pipe failure. Other water quality factors may also affect the chlorine decay and internal corrosion rate in cast iron pipes.

Kiene et al. (1998) and Zhang et al. (2008) identify the relative impact of a number of factors including synthetic pipes, Total Organic Carbon concentrations (TOC) at common temperatures and pH levels, and the amount of fixed biomass, on the degree of chlorine decay in water distribution pipes. They show that the chlorine consumption by synthetic pipe material (e.g., Polyvinyl Chloride) is negligible and does not appear to be an important factor for modeling of chlorine decay. They also show that the chlorine decay due to the bulk water reaction is quite variable depending on the organic matter concentration (TOC). For waters at common temperatures and pH levels, higher TOC values may cause higher chlorine decay and may increase the probability of failure due to the internal corrosion over time.

Chlorine decay due to fixed biomass varies according to the colonization time and reaches a stationary state after a given period of time which depends on the water quality factors such as pH and temperature (Keine et al. 1998). The fixed biomass may also directly affect the rate of internal corrosion in a cast iron pipe. The fixed biomass attached to the pipe wall may act as a protective property that reduces the corrosion rate of a pipe segment and eventually decreases the probability of failure due to the internal corrosion (Hallem et al. 2001).

5.3.3 Asset management

Major lifetime costs of water distribution systems are the costs of the loss of water and of the pipe repairs and replacement needed to prevent leaks. Utilities typically believe that much of this expenditure is related to the ageing pipes that have suffered from external corrosion throughout the pipe exposure time. While external corrosion significantly affects the likelihood of mechanical failure, this research has shown that the risk of failure may be further heightened if internal corrosion is occurring. Therefore, some mitigation practices must also be examined to prevent further risk of failure due to internal corrosion, and this explains the popularity of pipe lining practices. The most effective methods of preventing internal corrosion in water mains include the application of a surface lining and the addition of inhibitors, e.g., chromate, nitrate, and phosphate (Snoeyink and Wagner 1996). Also, the application of surface coatings and the use of cathodic protection to control the external corrosion are recommended (Baeckmann et al. 1997). A future improvement of the models developed herein, is to investigate their application for determining the value of such practices so as to evaluate the cost-benefit analysis of implementation of these.

5.3.4 Improvement to the model

The methodology developed herein has several limitations. Modifying the external and internal corrosion models is the first step to the applicability of the model in practice. While external corrosion has been shown to significantly affect the likelihood of mechanical failure, it is also shown in this study that the risk of failure may be further heightened if internal corrosion is occurring. The sensitivity analysis of variables influencing the overall probability of pipe failure indicates that some parameters related to the internal corrosion model (e.g., C_t/C_0, K, V) and some related to the external corrosion model (e.g., the pitting depth scaling factor, b) are significant in comparison with the other variables related to environmental and other operationally-imposed stresses. Therefore, the results of the sensitivity analysis suggest that future research should invest the greatest effort in further improving and validating the internal and external corrosion models. In other words, high sensitivity of corrosion model parameters point to a conclusion that in crafting physical models for pipe failure, the biggest effort should be invested in refining the internal and external corrosion models and their parameters.

5.3.5 System reliability

Generally, utilities are interested in two types of system reliability. The first type is mechanical system reliability which relates to the operability of equipment (e.g., pipes, valves, pumps, and tanks) in water distribution systems. Although pipe breakage is one of the most common mechanical failure modes in such systems, the probability of failure of other equipment and their replacement costs should be considered in evaluating reliability of a water distribution system. The second type is hydraulic system reliability in which utilities have to consistently provide the specified amount of water (e.g., minimum consumer demand) at required pressures (e.g., minimum pressures for consumers and fire demand purposes) at the time and location desired. In addition to these factors, investigating system reliability increases the need to evaluate systems with time-dependent variables, since not only do demands, supplies, flows, and chlorine concentrations vary with time in such systems.

In this research, the probability of failure analysis is estimated for a given pipe segment with a specific length and diameter. For applicability in practice, the overall probability of failure due to corrosion for a water distribution system (mechanical system reliability) with various pipe lengths and diameters needs to be estimated. There are some analytical techniques that may be used to estimate the system reliability including the Cut-set, Tie-set, Event tree, and Fault tree methods (Henley and Kumamoto 1981; Dhillon and Singh 1981; Hwang et al. 1981).

5.3.6 Selection of parameters to reflect real world engineering

Often, data required to define probability distribution functions are not available and therefore pre-defined distributions based on limited information are used to estimate the probability of failure. However, the selection of parameters may not reflect those that relate to real-world engineering and thus may limit the applicability of the model results. For example, most small pipes in water distribution systems (e.g., D < 200 mm) are oversized in order to have sufficient capacity under fire flow conditions and therefore under normal circumstances pass flows well below their capacity causing low water velocity, often less than 0.1 m/s. In this situation, the lower velocity leads to lower corrosion rates based on Equation 2.9 and thus decreases the probability of failure over time (in this case the probability estimation conducted in this study is in conservative) and the importance of internal corrosion is reduced relative to external corrosion . Similarly, higher velocities may increase the corrosion rate and the probability of failure based on Equation 2.9. The explanation for this is that as high velocities cause sloughing of the corrosion products built on the pipe wall, a new surface will be in contact with free chlorine residual, and lead to higher consumption of chlorine and consequently higher internal corrosion rates.

The selected values of chlorine concentration used in this study may be different from those in practice. The minimum value for the chlorine concentration is considered herein to be 0.5 mg/l (based on the assumption that this minimum concentration of chlorine disinfects the water) and the maximum value to be 1.3 mg/l (based on the assumption that higher concentrations lead to the production of chlorine byproducts that pose risks to human health). In practice, there is a wide range of chlorine concentrations in water distribution systems from 0.2 mg/l to 2 mg/l. This may significantly alter the results of this research because of its importance in determining the overall probability of failure.

While the selection of appropriate ranges or distribution functions for some variables is relatively straightforward, the selection of these distributions for other variables (e.g., environmental loads or external corrosion) is difficult to define. Therefore, in future research a comprehensive study is needed to select all the variables with appropriate distributions to be applicable in practice and to reflect the behavior of a real system.

5.4 CONCLUSIONS

The concentration of chlorine residual can affect the internal corrosion rate and contribute to pipe mechanical failure. Considering the effect of internal corrosion on the pipe failure, a probabilistic analysis is used to estimate the probability of mechanical failure over the exposure time. Considering the first failure mode defined in Chapter 2, the likelihood of failure increases to nearly 50% in the 80th year of pipe age. Considering the second failure mode defined in

Chapter 3, which allows for a comparison to be made with the failure mode defined by Sadiq et al. (2004) (for estimating the probability of failure due to only external corrosion), the likelihood of failure also increases to nearly 50% in the 110th year of pipe age. The results indicate that the effect of internal corrosion on mechanical failure is lower, but on the same order of magnitude, as the effect of external corrosion on such failures. Sadiq et al. (2004) estimated a 50% likelihood of failure in the 70th year of pipe age in the case of external corrosion for the same type of pipe, i.e., 6.1 m pipe length and 203 mm diameter.

Environmental, i.e., loads due to the earth, traffic, frost, and operational loads, i.e., water pressure, can affect the external corrosion rate and contribute to pipe mechanical failure. The results of the probabilistic analysis indicate that the likelihood of failure of a cast iron pipe due to both internal and external corrosion is nearly 50% by the 45th year of exposure.

The first indicator of pipe condition has been identified as the number of pipe breaks throughout the exposure time. Chapter 4 estimates the cumulative number of pipe failure per 1000 m of cast iron pipe. The results show how the number of failure increases throughout the exposure time. For example, after 45 years of pipe installation, the cumulative number of pipe breaks is about 100. The likelihood of failure for a given residual pipe wall thickness for a given exposure time is estimated in Chapter 4. It may be considered as the second indicator of pipe condition. For example, for the 45 years old of a pipe segment with the 12mm original wall thickness, the likelihood of failure is about 50% when the residual pipe wall thickness is about 7.8mm.

To validate the estimates, the survival function is estimated based on the continuous probability density and hazard functions determined in Chapter 4. The estimated survival function compares well with those determined by Pelletier et al. (2003) for cast iron pipes with diameters of between 100 and 200 mm based on pipe break data for the municipalities of Chicoutimi, Gatineau and Saint-Georges, Quebec.

5.5 FUTURE WORK

Further studies that may be beneficial include the following:

- Considering other water quality factors that can affect the internal corrosion rate and may contribute to pipe mechanical failure, i.e., pH, alkalinity, and the amount of fixed biomass;

- expanding the performance function to include other modes of failure due to the internal corrosion, most importantly water quality failure due to the release of corrosion products, e.g., contributing to red water;
- considering different possible corrosion models rather than the linear corrosion model with a constant rate, to explain the behavior of the internal corrosion rate;
- expanding the performance function to include the sudden changes of water pressure, e.g., water hammer, in a pipe segment to estimate the probability of failure due to internal and external corrosion;
- performing economic evaluations to determine an optimum replacement time for water mains that are failing due to both external and internal corrosion and budgetary needs for future repairs under various replacement and rehabilitation strategies;
- expanding the probability analysis for different pipe materials and diameters;
- obtaining an estimate of system reliability of the pipe network by assessing the potential network failure due to internal and external corrosion instead of analyzing only a single pipe segment.

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Yamini, H. and Lence, B.J. (2009a) "Probability of Failure Analysis due to Internal Corrosion in Cast Iron Pipes." Accepted for publication in *ASCE Journal of Infrastructure Systems*, IS/2007/022664. In print for December issue.

Yamini, H. and Lence, B.J, (2009b) "Probability of Failure Analysis due to Internal and External Corrosion in Cast Iron Pipes" Accepted in *ASCE Journal of Infrastructure Systems*, IS/2007/022729.

Yamini, H. and Lence, B.J, (2009c) "Condition Assessment of Cast Iron Pipes in Water Distribution Systems." Submitted to *ASCE Journal of Infrastructure Systems.*

APPENDIX A: List of publications

This thesis has led to the following publications:

- Yamini, H. and Lence, B.J. (2007). ” Probability of Failure Analysis due to Internal Corrosion in Cast Iron Pipes. *ASCE Journal of Infrastructure Systems. In print.*

- Yamini, H. and Lence, B.J, (2008). "Probability of Failure Analysis due to Internal and External Corrosion in Cast Iron Pipes."

- Yamini, H., and Lence, B. J. (2008). "Condition Assessment in Cast Iron Pipes in Water Distribution Systems.

- Yamini, H., and Lence, B. J. (2007). "Probability of Failure Analysis due to Internal Corrosion in Cast Iron Pipes." *ASCE Conference Proceedings, 8th Annual Water Distribution System Analysis Symposium*, Editors: Buchberger, S., Clark, R., Greyman, W., Uber, J. Page 27.