A methodology to estimate remaining service life of grey cast iron water mains

Balvant Rajani and Jon Makar

Abstract: The decision to repair, renew, or replace existing old grey cast iron mains is typically based on performance indicators such as structural integrity, hydraulic efficiency, system reliability, and water quality. Structural integrity (often quantified as the number of main breaks per kilometre or mile per year) is the most common performance indicator. However, these indicators represent past performance, rather than expected future performance. Decisions based on performance indicators may not, therefore, accurately meet the real needs of the utility owner of the water distribution system. A preferred approach to make decisions on pipe repair and replacement is to determine the expected remaining service (residual) life of each pipe segment and ensure that the necessary work is performed before failure occurs. Past efforts to estimate remaining service life of water mains have been based on corrosion pit depth and estimated corrosion rate with no regard to the influence of corrosion on the structural resistance capacity of water mains. This paper describes a methodology to estimate the remaining service life of grey cast iron mains that takes corrosion pit induced changes in the structural resistance capacity into account. The methodology combines the residual resistance capacity of grey cast iron mains, anticipated corrosion rates, and the measurement of corrosion pits by direct inspection or non-destructive evaluation technology to predict when the factor of safety of an individual pipe segment will fall below a minimum acceptable value set by the utility owner, i.e., remaining service life. The estimate of remaining service life may then be used to schedule appropriate maintenance or replacement of grey cast iron mains.

Key words: water mains, remaining service life, residual life, repair, renew, or rehabilitate water mains, corrosion models, pit and spun grey cast iron.

Résumé : La décision de réparer, renouveler ou remplacer de vielles canalisations en fonte grise est typiquement basée sur des indicateurs de performance tels que l'intégrité structurale, l'efficacité hydraulique, la fiabilité du système et la qualité de l'eau. L'intégrité structurale (souvent décrite comme le nombre de fissures majeures par kilomètre ou mille par an) est le plus commun des indicateurs de performance. Cependant, ces indicateurs représentent la performance passée plutôt que la performance future espérée. Les décisions basées sur les indicateurs de performances peuvent donc ne pas subvenir précisément aux besoins réels du propriétaire du système de distribution d'eau. Une approche préférée afin de prendre des décisions sur la réparation et le remplacement de conduites est de déterminer la durée de service restante (résiduelle) espérée de chaque segment de conduite et de s'assurer que les travaux nécessaires sont accomplis avant que la défaillance n'apparaisse. Les précédents efforts pour estimer la durée de service restante de canalisations d'eau ont été basés sur la profondeur des trous dus à la corrosion et le taux de corrosion estimé, sans considérer l'influence de la corrosion sur la capacité structurale des canalisations d'eau. Cet article décrit une méthodologie pour estimer la durée de service restante de canalisations en fonte grise, qui prend en considération les changements de la capacité de résistance structurale induits par les trous dus à la corrosion. La méthodologie combine la capacité de résistance résiduelle de canalisations en fonte grise, les taux de corrosion anticipés, et la mesure de trous dus à la corrosion par le biais d'une inspection directe ou par une technologie d'évaluation non destructive, ceci afin de prédire quand le facteur de sécurité d'un segment de conduite individuel va tomber en-dessous d'une valeur minimale acceptable établie par le propriétaire de l'infrastructure (c'est-à-dire la durée de service restante). L'estimation de la durée de service restante peut par la suite être employée pour planifier la maintenance ou le remplacement approprié des canalisations en fonte grise.

Mots clés : canalisations d'eau, durée de service restante, durée résiduelle, réparation, canalisations d'eau renouvelées ou réhabilitées, modèles de corrosion, fonte grise troué et tordue.

[Traduit par la Rédaction]

Received October 22, 1999. Revised manuscript accepted July 13, 2000.

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Written discussion of this article is welcomed and will be received by the Editor until April 30, 2001.

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Introduction

Water utilities in Canada (Canadian Water and Wastewater Association 1997) and in the United States (Kirmeyer 1994) invest in water mains at an average annual rate of 0.6% and 0.5%, respectively, of the replacement value of their water distribution systems. Much of this expenditure is to maintain or replace ageing grey cast iron distribution mains and transmission lines. Kirmeyer et al. (1994) estimated in 1992 that 48% of all existing water pipes in the United States were grey cast iron. A survey of 21 Canadian cities (11% of the population) conducted by Rajani and McDonald (1995) revealed a similar percentage of grey cast iron pipes. These grey cast iron pipes are also the oldest pipes in most water distribution systems. Grey cast iron has a tendency to corrode in aggressive environmental conditions, which leads to the development of corrosion pits or graphitized areas that reduce the resistance capacity of individual pipe segments (typical length of a single pipe varies between 3.05 m (10 ft) and 6.1 m (20 ft)). This susceptibility of grey cast iron pipes to corrosion results in an acceleration of failures as pipes age (O'Day et al. 1986). Since water utilities must repair, rehabilitate, or replace these failed water mains, the requirement for expenditures on pipe maintenance have also increased with time.

Decisions on pipe maintenance are typically based on performance indicators (Deb et al. 1995) that determine the adequacy of water supply in a distribution system. These indicators are structural integrity, hydraulic efficiency, system reliability, and water quality. The capability of a section of distribution system to deliver potable water is typically determined on the basis of its hydraulic capacity and water quality. Decisions on repairs and replacements are usually made based on structural integrity and system reliability. These decisions are often made using measures such as the number of water main breaks per kilometre (or mile) per year. Many water utilities investigate any segment of the water distribution system that fails to meet set performance criteria for any one of the four indicators. This investigation typically determines whether the water main requires immediate attention. If this is not the case, the investigation will then determine how long the appropriate response (repair/renewal/replacement) can be deferred.

These indicators indicate only the past and current performance of the segment, rather than how it will behave in the future. Decisions to undertake any one of these actions therefore depend largely on criteria based on past performance rather than on predicted future performance. Consequently, utilities need to undertake a rational approach to establish repair, rehabilitation, and replacement priorities among the different pipe sections (portion of the water distribution system between two valves) of the water distribution system at any given time. Such an approach should consider not only current pipe performance, but also expected future performance. A preferable alternative approach would be to base decisions on the actual remaining service life of each individual pipe segment. The principal benefits of using a methodology to estimate remaining service life or factor of safety of grey cast iron water are

- prioritization of replacement and renewal programs for grey cast iron water mains through a rational, comprehensive performance approach
- reduced frequency and severity of water main breaks, leading to improved customer service
- the ability to assess the impact of corrosion pits on the remaining service life of the grey cast iron water mains
- the ability to assess the effectiveness of mitigating measures, such as cathodic protection, to extend the life of water mains

The methodology can therefore assist in making proactive decisions based on the expected future behaviour of each segment or section and on improved water utility planning. It will help to ensure that maintenance and renewal budgets are spent where they are most needed.

Previous efforts (Doleac et al. 1980; Randall-Smith et al. 1992) to estimate remaining service or residual life of water mains have been based on corrosion pit depth and estimated pit growth rate (henceforth referred to as corrosion rate) without regard to the resulting reduction in structural resistance capacity of water mains. In addition, corrosion was regarded as a process that is constant, rather than one that is known to be non-linear but difficult to model.

This paper describes a methodology to estimate remaining service life of grey cast iron mains that accounts for both the influence of corrosion pits on structural resistance capacity of water mains and changes in anticipated corrosion growth pit rates. The methodology assumes that the primary cause of in-service pipe failures is corrosion pitting. Consequently, the proposed methodology will permit the water utility to determine when the factor of safety will fall below 1, i.e., to use the time at which the mains are in a state of imminent failure as an estimate of the remaining service life. The water utilities will need to gather extensive information on their water distribution systems to implement the methodology. Information collected on pipe segments and sections will typically include the size of corrosion pits in operating pipes, the mechanical properties of grey cast iron, the acting internal pressures and external loads, and the expected corrosion rates. In general, substitute values for mechanical properties (Rajani et al. 2000) of grey cast iron mains of the same age and from the same manufacturing source can be used if data for the specific pipe segment or section are not readily available. Estimates of expected internal pressures and external loads can be obtained from records of recent measurements (operating conditions) and design standards C101-67 (AWWA 1977), respectively. However, direct or indirect measurements of corrosion pits are essential. Commercial non-destructive testing (NDT) technologies (Staples 1996) that measure pit depths have recently been developed. Experimental work has also indicated that the same techniques can be used to measure all three-dimensional characteristics of corrosion pits (Rajani et al. 2000).

Technical approach

Background

Ideally, a buried pipe should maintain its original factor of safety throughout the life of the distribution system. C101-67 (1977) advocated the design of water mains with a factor of safety 2.5 for flexural and tensile stresses. The factor of safety of the pipe is the ratio of admissible or allowable stresses. However, life of the pipe begins to decrease as soon as the pipe is installed because aggressive environmental conditions (e.g., water quality, soil type, soil aggressivity, ground water conditions, and stray currents) attack unprotected buried metallic pipes through the mechanisms of internal and external corrosion. Details on mechanisms of how these conditions influence corrosion are well known as described by Peabody (1977). Corrosion pits can develop randomly along any segment of water main. These pits have a variety of shapes with characteristic depths, diameters (or widths), and lengths. They tend to grow with time at a rate that depends on environmental conditions in the immediate vicinity of the water main. The presence and size of corrosion pits in a buried pipe undermine its resistance capacity, which in turn reduces the factor of safety of the water distribution system.

The methodology to estimate remaining service life of grey cast iron mains requires the determination of how a growing corrosion pit affects the strength or pipe resistance capacity of an individual pipe segment. Change in resistance capacity of grey cast iron mains due to the presence of corrosion pits can be determined by one of two approaches:

- A rigorous structural analysis that incorporates all measured geometrical characteristics of corrosion pits and mechanical properties of intact pipe material may be performed for each pipe segment. This approach requires a re-analysis each time the geometry of an individual pit is measured. Finite element methods are typically used for this type of analysis to ease the incorporation of complex pit shapes, sizes, and boundary conditions. Although this approach is sometimes used for oil and gas transmission lines, it may be impractical for water distribution systems, since it is computationally intensive. As a result, substantial effort and expense would be required for the analysis of a distribution system that can extend hundreds of kilometres or miles.
- An alternative approach is to assess the residual tensile strength as a function of size and geometrical characteristics of corrosion pits present in the pipe under acting stresses. It therefore does not represent the strength of the material itself, but rather indicates the weakening produced by the corrosion pit. Existing design methods (C101-67 1977) for new distribution systems can be used to determine the reduced pipe factor of safety provided that acting stresses are compared to the reduced rather than the original pipe resistance capacity. Another significant difference between this and the previous approach is the use of nominal or remote stresses rather than localized stresses acting in the region of corrosion pits. Nominal stresses are calculated assuming that the pipe is free of corrosion pits and acts as a beam, column, or ring or combination thereof. Localized stresses result as a consequence of stress concentration effects in the presence of corrosion pits. A method using nominal stress is particularly suitable for experimental analysis, since it allows for mechanical testing of pipe samples or coupons from water mains with corrosion pits of different sizes and shapes. This approach is advocated by B31G-1991 (ASME 1991) for the determination of the residual strength of corroded oil and gas pipelines.

The approach outlined in ASME B31G (1991) is based on mechanical full-scale burst tests on representative corroded steel pipe samples or segments subjected to internal pressure. It is important to note that ASME B31G (1991) deals with steel rather than cast iron, which is of interest here. Several hundred full-scale burst tests on actual field (corroded) specimens were conducted to establish a relationship between the size of corrosion defects and failure pressures of steel pipe. However, costs associated with these burst tests can be high. Instead, a variety of simple mechanical tests (tensile, four-point bending, ring, and fracture toughness tests) were used as substitutes to evaluate the influence of defect size on grey cast iron water mains. These mechanical tests led to an empirical relationship between residual tensile strength and defect characteristics shown in Fig. 1 as curve U. This relationship defines two zones, i.e., an admissible zone below curve U where the pipe is safe and an inadmissible zone above curve U where the pipe will fail. Details on the tests and how this relationship was established are given in Rajani et al. (2000).

Design procedures for grey cast iron water mains

The design procedure for grey cast iron mains as outlined in C101-67 (AWWA 1977) considers a pipe as a rigid structural element. Rigid pipes support loads by virtue of resistance of the pipe as a ring to bending and do not rely on horizontal thrust from the soil at the sides. Experimental work done by Schlick (1940) showed that failure of a grey cast iron pipe under combined internal pressure (p) and an external three-edge (bearing) ring load (w) will not occur if

$$[1] \qquad \left(\frac{w}{W}\right)^2 + \left(\frac{p}{P}\right) \le 1$$

where W is the three-edge crushing (ring) load necessary to cause failure in the absence of internal pressure, and P is the internal bursting pressure necessary to cause failure in the absence of external load. The factor of safety need not be identical for internal pressure and external three-edge load, though the design standard suggests a common value of 2.5. W and P are determined on the basis of hoop stress as follows:

$$[2] \qquad W = \frac{\pi h^2 \sigma_r}{3(D+h)}$$

$$[3] \qquad P = \frac{2h\sigma_t}{D}$$

where h and D are pipe wall thickness and internal diameter, respectively, σ_r is the “rupture modulus” and σ_t is the “bursting tensile strength.” The rupture modulus represents the local flexural or bending action along the ring whereas the burst tensile strength represents the hoop tension in the grey cast iron pipe.

The pipe design procedure uses known earth loads and internal pressures to determine the minimum wall thickness for a pipe of a specific diameter that will give the desired factor of safety. Earth loads are typically determined for two conditions, i.e., case 1A: earth load (W_e) only, and case 2A: earth and truck (W_t) loads. Similarly, two operational conditions are considered for internal pressure, namely, case 1B: internal pressure, and case 2B: internal and surge pressures. Specific equations and variables required for calculating these loads are given in C101-67 (AWWA 1977). The mini-

Fig. 1. Influence of corrosion pit dimensions on resistance of grey cast iron water mains.

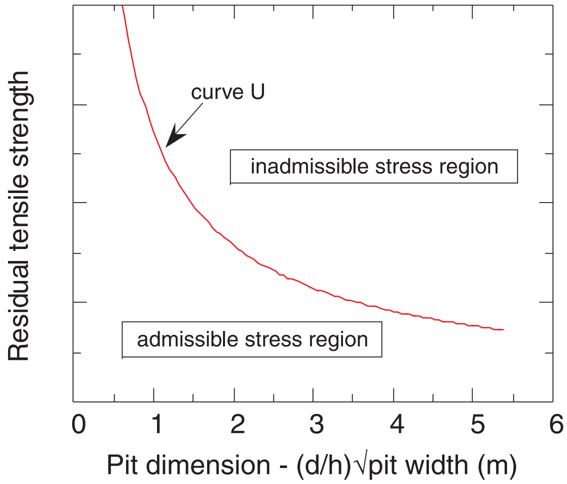
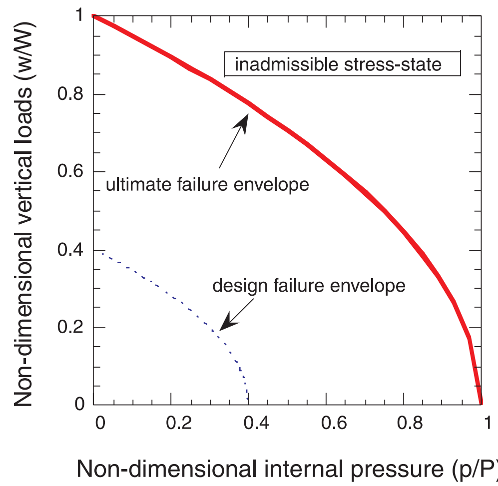


Fig. 2. Stress-state diagram for grey cast iron under operational loads.



mum pipe wall thickness for a selected pipe diameter must have an acceptable safety factor for these combined load conditions : (*i*) only surge pressure and no truck superload and (*ii*) only truck superload and no surge pressure. These combined loads are selected on the likelihood that surge pressures and truck superloads are very unlikely to act concurrently because of their transient nature.

Stress-state at any location in the grey cast iron water mains can be represented by (w/W, p/P) (Fig. 2) as indicated in eq. [1]. In this case, stress-state accounts for operational and local environmental conditions. All stress-state points should lie below the design failure envelope when water mains are free from corrosion pits. In the event that truck loads or internal pressures are higher than anticipated in design, stress-states will move beyond the design failure envelope but below the ultimate failure envelope. Of course, if the stress-state reaches beyond the ultimate failure envelope, failure will occur. However, stress-state within the pipe can also change even if the pipe is subjected to unanticipated loads. This situation arises when corrosion pits reduce the resistance capacity of the pipe. Corrosion pit dimensions will determine if the stress-state lies beyond design failure or ultimate failure envelopes.

Modifications to existing design procedure

The design procedure as stated in C101-67 (AWWA 1977) needs modification to include grey cast iron mains that have corrosion pits. Buried water mains are subjected to thermal (largely a consequence of the difference in water temperature and ground temperature), internal pressure, earth, frost, and traffic loads. The C101-67 design procedure does not include thermal and frost load effects. However, recent research (Rajani et al. 1996; Rajani and Zhan 1996) has improved the understanding of these issues, which make it possible to incorporate these effects in the proposed methodology as modifications to the original design procedure.

Effects of corrosion pits on pipe resistance capacity

As discussed earlier, pipe resistance is reduced by the presence of corrosion pits. Rajani et al. (2000) established that the residual tensile strength of grey cast iron mains is empirically related to pit dimensions as described by the following relationships:

$$[4] \qquad \sigma_n = \frac{\alpha K_q}{\beta[(d/h)\sqrt{a_n}\,]^s}$$

$$[5] \qquad \beta^{\text{upper}} = 0.5(d/h)^{-0.3} \text{ and } \beta^{\text{lower}} = 0.3(d/h)^{-0.2}$$

Equation [4] is essentially the same basic fracture mechanics equation that relates stress, defect size, and geometry through stress intensity or toughness of the material. This expression describes the relationship among the nominal tensile stress (σ_n) at which fracture takes place, corrosion pit size (lateral dimension, a_n), provisional fracture toughness (K_q) of the material, and a geometric factor (β) dependent on the dimensions and shape of the corrosion pit (eq. [5]). The expression is modified via constants α, s, and pit depth/pipe wall thickness ratio (d/h) on an empirical basis to include pits that are not "through or full penetration," sharp, and of ideal shape. Two types of cast iron used for mains were produced: pit cast (1908–1967) and spun cast (1953–1982). Parameters α and s are found to be independent of grey cast iron type, and consequently fracture toughness (K_q) values can be used as the distinguishing material property. Details of selection of parameters α and s are given by Rajani et al. (2000). A reduction factor (f_r) is defined as the ratio of residual strength to the measured tensile strength of the same grey cast iron mains without any defects. The use of minimum tensile strength as specified by the manufacturer can lead to an underestimate of pipe resistance, as the actual value may be much higher. The reduction factor (f_r) is applied to the design or measured tensile (σ_t) and rupture modulus (σ_r) in eqs. [2] and [3]. This modification essentially changes crushing load (W) and bursting failure pressure (P) in the denominator of eq. [1].

Thermal effects

The thickness design method (C101-67) does not explicitly consider the influence of the temperature difference between water in the mains and surrounding soil. However, this difference can lead to further reduction in the factor of safety as it induces axial stresses. Water mains may break in the circular or longitudinal failure modes if induced stresses exceed the axial tensile strength. A circular break is evidence that a longitudinal tensile stress condition caused this type of failure. A longitudinal break is a result of circumferential or hoop stress and (or) in-plane bending action. The failure mode is dependent on the specific pipe size, trench geometry, soil, and environmental and operational conditions. Longitudinal tensile stresses in water mains may be induced through restrained movement by the frictional resistance between pipe and soil as the pipe expands and contracts subjected to a temperature differential between water and surrounding soil. Flexural (bending) action due to inadequate bedding support or swelling of underlying clays imposes additional longitudinal tensile stresses. Large hoop stresses can arise as a result of either pressures exerted by an increase in volume when water freezes or large surge pressures. Rajani et al. (1996) developed an analytical solution for a pipe of any material under pressure subjected to thermal and other operational loads. The analytical solution can be simplified specifically for a metallic pipe, where the ratio between the soil elastic modulus and pipe material elastic modulus is very small. Consequently, the external pressure due to the soil reaction can be taken as zero. As a further simplification, the interface between the pipe and soil is taken as fully bonded, since that situation is the worst case scenario for stress induced in water mains. These simplifications lead to the following equations for the axial and hoop stresses:

[6] $$\sigma_x = -E_p \alpha_p \Delta T + \frac{v_p D}{2h} p - \frac{v_p}{2} p$$

[7] $$\sigma_\theta = \frac{D}{2h} p$$

where σ_x, and σ_θ are the axial and hoop stresses, α_p, v_p, E_p are linear thermal expansion coefficient, Poisson ratio, and elastic modulus of the pipe material, respectively, ΔT is the maximum likely temperature difference between water temperature and surrounding soil, D and h are pipe diameter and wall thickness, respectively, and p is pipe internal pressure.

Frost load effects

Procedures to determine earth and traffic loads are given in C101-67, which, however, lacks a procedure to calculate frost load. Frost load can be determined (Rajani and Zhan 1996) as a function of trench width, frost depth penetration, and other soil properties. Alternatively, it can be estimated as a multiple of the earth load, which is the simplest way to take into account frost load. The frost load multiple (f_{frost}) is typically between 1 and 2. A value of 1 corresponds to the condition when there is no frost load and value of 2 corresponds to the condition of maximum frost load.

Axial and hoop stresses generated in the pipe under traffic, earth, and frost loads are tensile and in-plane flexural stresses (ring). These stresses are adjusted in accordance with bedding conditions (C101-67 1977) for grey cast iron mains and are calculated as follows:

[8] $$\sigma_x = v_p \frac{3D}{\pi h^2} w$$

[9] $$\sigma_\theta = \frac{3D}{\pi h^2} w$$

where w is the bearing ring load (combined cases 1 and 2) per unit length.

Failure criterion

Total axial and hoop stresses are determined by combining the effects of temperature and internal pressure equations ([6] and [7]) and external vertical loads equations ([8] and [9]).

The design method as described in C101-67 emphasizes ring (hoop or in-plane) stress, not axial stress. A failure criterion that reflects circumferential breaks needs, therefore, to be incorporated in the modified design procedure to account for all possible modes of failure. The failure criterion for stresses in the longitudinal direction is considered to be independent of the failure criterion for in-plane stresses (tension and flexion) expressed in eq. [1]. Failure will not occur if

[10] $$(\sigma_x / \sigma_y) \le 1$$

where σ_x and σ_y are total axial stress (eq. [10]) and uniaxial tensile strength, respectively. Therefore, a distinct design criterion for axial stresses described in eq. [10] is proposed in addition to the criterion expressed in eq. [1].

Calculation of remaining service or residual life

The strategy is to estimate the remaining service life (t_{residual}) so that pit dimensions (pit depth (p_{depth}), width (p_θ), and length (p_x)) at that time just satisfy the failure criteria as specified by eqs. [1] or [10].

The water utility will need to estimate external corrosion rates in terms of pit depth growth around the mains to be analysed. If these data are not available then it is recommended that the water utility establish a data gathering program or use general models developed elsewhere (Romanoff 1964; Rossum 1969; Rajani et al. 2000) to predict corrosion pit growth rates. The Rossum and exponential corrosion (Rajani et al. 2000) models are presented in eqs. [11] and [12] for completeness

[11] $$p_c = K_n z^n$$

where

$$z = \left[\frac{(10 - \text{pH})t}{\rho_{\text{soil}}} \right]$$

and

[12] $$P_c = at + b(1 - e^{-ct})$$

where p_c is corrosion pit dimension, ρ_{soil} is soil resistivity, pH is soil acidity/alkalinity, and n is soil redox potential represented by a soil aeration constant and a, b, c and K_n are constants. The relationships (eqs. [11] and [12]) that describe the growth of corrosion pits are based exclusively on pit depth, not on pit width or length. It is assumed that the corrosion pit growth rate relationships applicable to pit depth are also applicable for predicting the growth of pit width, depth, and length unless independent data are available to show otherwise. The pit dimensions (r_g) at any time

(t) after the pit dimensions, r_{inspect}, determined at inspection time, t_{inspect}, can be stated as

$$[13] \qquad r_g = r_{\mathrm{inspect}} \frac{f(\ldots, K_n, n, t)}{f(\ldots, K_n, n, t_{\mathrm{inspect}})}$$

where the function, f, represents any relationship represented by eqs. [11] or [12]. The generalized variable, r_g, has been used to describe any of the pit dimensions (pit depth (p_{depth}), width (p_θ), and length (p_x)) in the above equation, since the pit is likely to grow in all directions with time.

The procedure to estimate time ($t_{\mathrm{FS_{fail}}}$) requires iteration with time, so that time dependent pit dimensions satisfy the structural failure condition as expressed by eq. [1] for the designated minimum factor of safety ($\mathrm{FS_{fail}}$). Therefore, the remaining service life (t_{residual}) of the grey cast iron mains is given by

$$[14] \qquad t_{\mathrm{residual}} = t_{\mathrm{FS_{fail}}} - L$$

where L is the time elapsed between the time of installation and inspection of the grey cast iron main. In this procedure, the resistance of grey cast iron pipe is effectively controlled by the size of the corrosion pits and all existing operational and environmental conditions remain unchanged.

The methodology

The methodology is based on establishing a base condition and an iterative procedure to estimate the remaining service life of segments of grey cast iron pipe. The block diagrams in Figs. 3–5 illustrate the three main components of the methodology, i.e., design of new pipe and “one-time” and “multiple-time” corrosion pit measurement options. Details on sub-components for corrosion pit measurements, structural condition assessment, and determining remaining service life of cast iron mains are provided first because they are common and essential to both one-time and multiple-time components or options.

Define the base condition of the main

A variety of background data are necessary to implement the methodology. These include

- pipe information (diameter, wall thickness, date of installation, depth of burial, and pipe type — spun or cast)
- soil condition (type, pH, density, resistivity, aeration quality)
- installation information (laying condition, load factor, coefficient of horizontal stress at rest, coefficient of sliding friction)
- operational conditions (water pressure, surge pressures, summer and winter air and water temperatures, wheel loads, vehicle impact factor, frost load factor)

The above information establishes the baseline information for all subsequent analyses and thus permits a comparative evaluation of the factors that influence the remaining service life of water mains. For instance, corroded pipe segments within the distribution system in a region of possible high surge pressures will have a significantly reduced factor of safety and hence a reduced remaining service life.

The water utility needs to decide on a value for the minimum factor of safety for each pipe segment in its system as part of the initial decision making process. A factor of safety of one signifies imminent failure. The water utility may wish to set a target factor of safety ($\mathrm{FS_{fail}}$) greater than 1, say 1.2, because it will provide leeway to repair or replace pipe segments before failure occurs. The acceptance of a lower factor of safety is only an interim measure to prioritize replacement and rehabilitation of mains. In fact, the factor of safety will only get lower with time as corrosion pits grow in the aggressive external environment.

Corrosion pit measurements

Two inspection approaches are feasible to determine corrosion pits characteristics of grey cast iron mains, namely, a direct approach using measurements taken by non-destructive evaluation (NDE) technology on operating pipes or an indirect approach where corrosion pit measurements are taken on exhumed pipe samples. In the direct approach, a non-destructive evaluation tool or probe is introduced into the grey cast iron mains through an entry point such as a fire hydrant to measure the location and principal dimensions of the corrosion pits. The most promising non-destructive technologies to size corrosion pits are ultrasound and remote field effect. A commercial tool based on remote field effect is available (Staples 1996) for measuring corrosion pit depths. It requires improved interpretation methods to accurately size individual corrosion pits for width and length. An NDE tool based on remote field effects is not affected by tuberculation. Ultrasonic inspection tools for water mains are under development. However, tests have shown that tuberculation may hamper or prevent water pipe inspections using ultrasonic methods. The indirect approach involves manual logging of the corrosion pits from grey cast iron pipe samples in accordance with G46-94 (ASTM 1996). These corrosion pits would then be assumed to be typical of all pipes in the immediate vicinity.

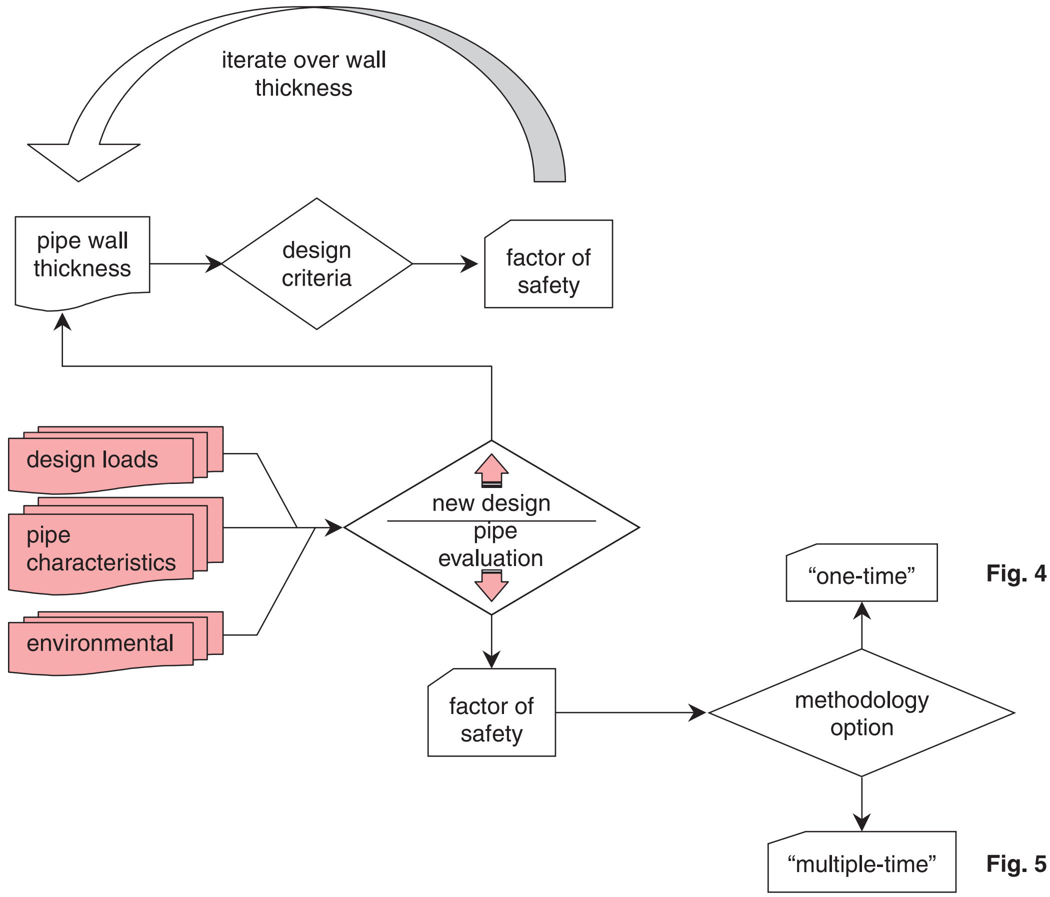
Tests on soil samples collected in the vicinity of the exhumed pipe samples give additional information to predict corrosion pit growth, as discussed earlier. Data from the indirect approach can then be used to empirically obtain corrosion pit characteristics for pipes of the same age and buried in the same soil type. Needless to say, direct measurement of corrosion pits using NDE is the more desirable approach.

Structural condition assessment of grey cast iron mains

The intent is to determine structural adequacy of pipes while accounting for the presence of corrosion pits. Therefore, if all environmental and operational conditions remain unchanged, the application of reduction factors to mechanical properties (tensile and bursting strengths) of grey cast iron for each corrosion pit in the water main will lead to a corresponding reduction in the factor of safety. Consequently, the factor of safety will tend to vary along the length of the mains. Points along the mains where the factor of safety is close to 1 or below 1 are the likely locations of water main breaks or leaks. Thus, individual grey cast iron segments can be identified as potential candidates for replacement or rehabilitation.

The mechanical properties (Table 1) of pipes being investigated can be based on the type of grey cast iron and on the installation date (Rajani et al. 2000). However, the preferred approach is to obtain mechanical properties from tests

Fig. 3. Methodology to estimate residual life grey cast iron water mains.



(Rajani et al. 2000) on samples removed from the water main segments that are of the same age and source of manufacture, because the mechanical properties of grey cast iron can vary widely one pipe segment to another. These data would be used to determine structural resistance capacity, such as that expressed in eqs.[2] and [3], and the residual tensile strength, as expressed in eq. [4].

Determination of remaining service life of grey cast iron mains

The determination of current factors of safety for the presence of significant corrosion pits is not sufficient to estimate the remaining service life of cast iron mains. Future growth of corrosion pits must also be predicted to determine when the pipe factor of safety will fall below 1. One-time pit measurement and multiple-time pit measurement options in the methodology are proposed to estimate the remaining service life of grey cast iron water mains. The one-time option is the better choice for an application of the proposed methodology when only a single pit measurement is made. This situation will arise if the indirect approach is used to measure corrosion pits or when the first time direct corrosion measurements are made on a given pipe segment. It uses estimates of the corrosion rate at a specific point along the water main to determine when a measured corrosion pit will grow to a size that reduces the pipe factor of safety below the desired limit. The multiple-time option is preferred when independent measurements of corrosion pit size made at the same locations at two or more distinct times are available. In this option growth rates of corrosion pits can be determined directly, making a more accurate evaluation of the remaining service life possible.

In the step-by-step descriptions of the one-time and multiple-time options, reference is made to labels (O-*x*) and (M-*x*), respectively, that refer to specific blocks in Figs. 4 and 5 where "*x*" refers to the step number.

One-time corrosion pit measurement option

The one-time option of the methodology (Fig. 4) is applicable when corrosion pit measurements are being taken for the first time. The reduced structural capacity, as a consequence of each major corrosion pit present in a grey cast iron water main, is calculated in this option. The future sizes of corrosion pits are then predicted based on the expected local corrosion rate, so that the time when the safety factor of the pipe falls below the target value set by the utilities may be determined, i.e., the remaining service life may be found. Specific steps (Fig. 4) are

(1) Segments of water mains under investigation are inspected (O-1a) for the presence of corrosion pits. If corrosion pits are present, their sizes are determined through direct (NDE) or indirect (pipe sampling) measurements. An associated stress-state (w/W, p/P) is then determined (O-1b) for each identified pit. If the stress-state for any of the pits results in a segment falling below the desired factor of safety (O-1c), i.e., exceeding

Fig. 4. "One-time pit measurement" to estimate residual life grey cast iron water mains.

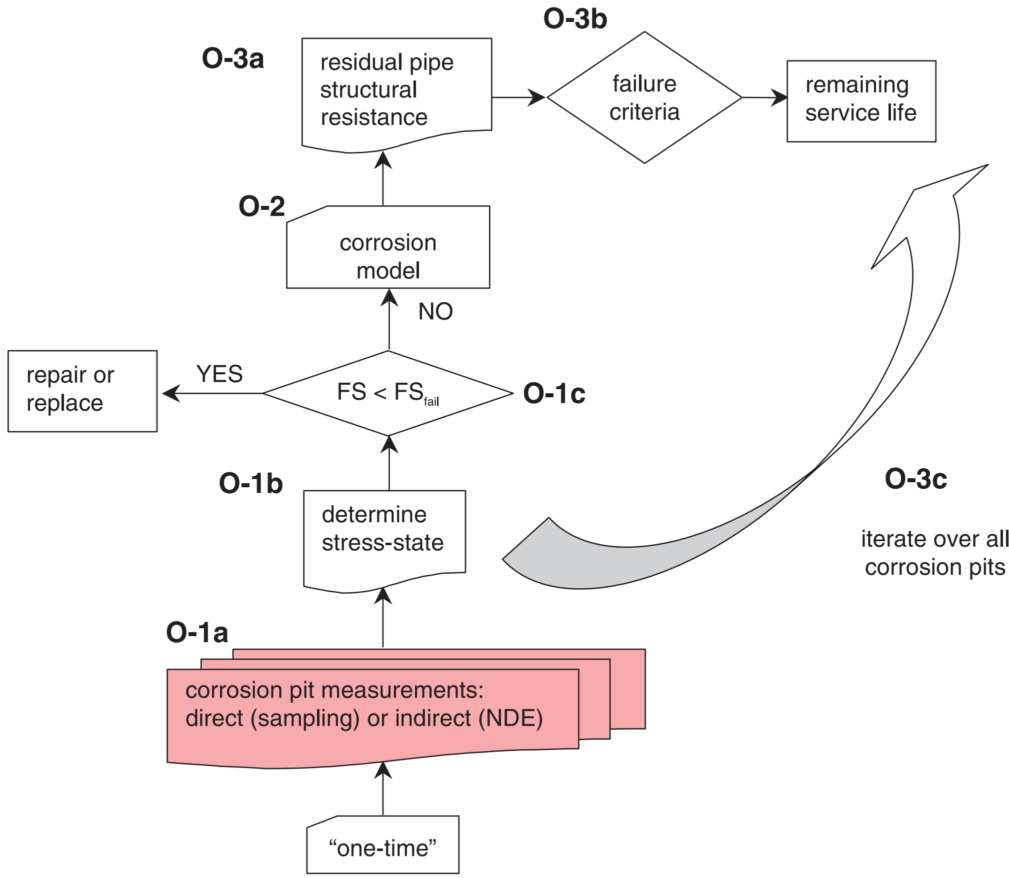


Fig. 5. "Multiple-time pit measurement" to estimate residual life grey cast iron water mains.

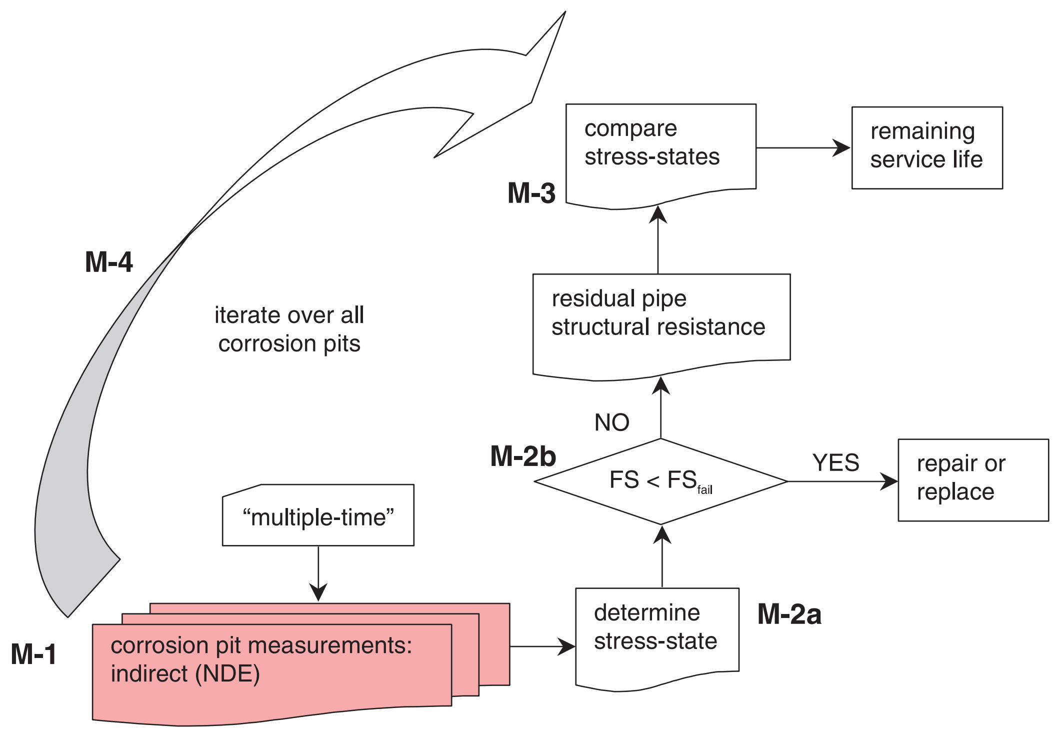


Table 1. Mechanical properties of grey cast iron mains.

Material	Reference	Duration	Tensile strength (MPa)	Modulus of rupture (MPa)	Fracture toughness (MPa√m)
Pit	7C.1-1908 (AWWA 1908)	1908 and 1952	138	248	—
Pit	A21.1-39 (AWWA 1939)	1939 and 1967	76	207–214	—
Pit	Rajani et al. (2000)	pipe age: 64–115 yr	33–267	132–378	5.7–13.7
Spun	C106-75 (AWWA 1975)	1953 and 1982	124	276	—
Spun	C106-75 (AWWA 1975)	1967 and 1982	145	310	—
Spun	Rajani et al. (2000)	pipe age: 22–51 yr	135–305	194–445	10.3–15.4

the ultimate failure envelope shown on Fig. 2, then that segment is in danger of failure and a decision on appropriate maintenance action is required. The stress-states for the remaining pits will be small enough that they fall well below the design failure envelope on Fig. 2 or will fall between the design and ultimate failure envelopes. The stress-state for corrosion pits that fall between the design envelope and the ultimate failure curves will present a more immediate risk of pipe failure.

(2) The local corrosion rate near the grey cast iron mains should then be determined (O-2) by one of two possible means, depending on resources available to the water utility. The first alternative is to measure corrosion pit dimensions (or average pit depth through weight-loss determination) and corrosion related soil properties to predict corrosion rates as described by eqs. [11] and [12]. The second alternative is to estimate corrosion rate based on regional estimates taken from measurements in similar environmental conditions.

(3) The next step is to combine the current dimensions of each significant corrosion pit, its expected growth rate, and the resulting reduced residual tensile strength (O-3a) to arrive at the time required for the factor of safety of the pipe segment to fall below the target value set by the utility. The time (remaining service life) to satisfy failure criteria (O-3b) specified in eqs. [1] and [14] can be calculated iteratively for each corrosion pit (O-3c) using eqs. [2]–[9], [11], [13], and [14]. The shortest time for all corrosion pits defines the remaining service life for the particular pipe segment. The pit that produces this shortest remaining service life is referred to below as the worst corrosion pit.

(4) The utility can then use this information together with other performance indicators (hydraulic efficiency, system reliability, and water quality) to establish priorities for its water main replacement. The remaining service life values calculated from corrosion pits other than the worst pit on a pipe segment can assist the utility to determine whether replacement or repair is the most economic maintenance option. If the other corrosion pits produce estimates of the remaining service life that are similar to that of the worst corrosion pit, then replacement is likely to be the most economical option. If the service life estimates are much longer than that of the worst pit, repair of the pipe is likely the best choice.

Multiple-time corrosion pit measurements option

Accuracy and predictability of corrosion rate of grey cast iron limit the application of the one-time option. The best approach is to use the one-time option described above to initiate implementation of the methodology and then return to use the multiple-time option. This approach provides a measurement of the actual growth rate of corrosion pits, producing an improved estimate of the remaining service life. The multiple-times option is applicable (Fig. 5) when corrosion pit measurements were made previously and current measurements from a second inspection have been obtained recently at the same location. Typically, these multiple-time pit measurements would be conducted using NDE tools. Current stress-states for significant corrosion pits are tracked and compared to the ones obtained from previous measurements. Specific steps (Fig. 5) are

(1) The second inspection or measurement of corrosion pit dimensions is conducted (M-1) at a subsequent time that is considerably less than the remaining service life estimated using the one-time option. This approach provides a measurement of the actual growth rate of corrosion pits and produces an improved estimate of the remaining service life. The time for the second inspection is based on inspection costs and estimated remaining service life obtained from the first application of the one-time option.

(2) Stress-states for each corrosion pit based on current pit dimensions are calculated (M-2a) after the second inspection. As with the one-time option, some of the corrosion pits may have a factor of safety less than the target value set (M-2b) by the utility and an immediate decision on maintenance for the segment will need to be taken.

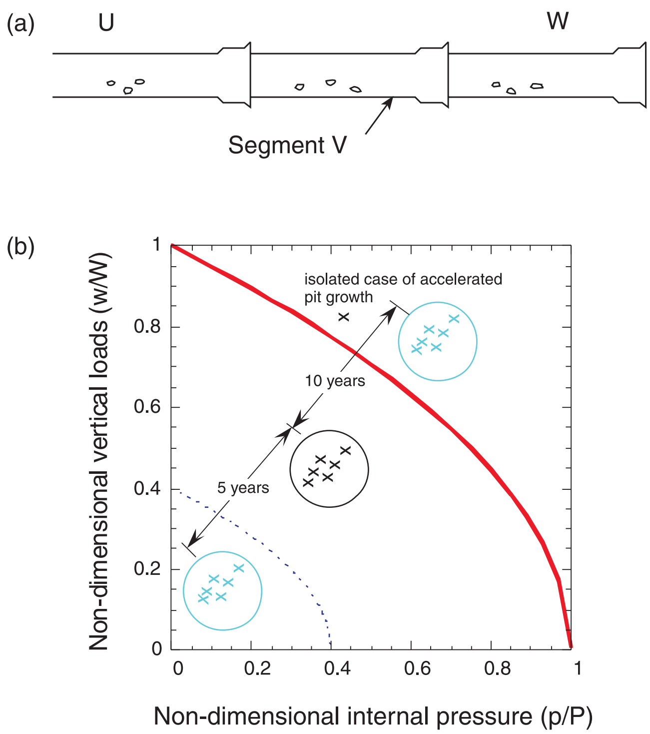
(3) A comparison of stress-states (M-3) between the current and previous inspections gives an indication of the corrosion rate. A closer proximity of the stress-states to the ultimate failure envelope indicates a reduced remaining service life of the water main.

(4) Successive inspections (Fig. 6*b*) of the same pipe segment over time will build up (M-4) a case history on the rate of deterioration of the water main. Tracking the rate of deterioration for individual pipe segments will allow the utility to estimate when a decision on maintenance action needs to be taken and to budget for that maintenance in advance with confidence. A decision on scheduling the next corrosion pit inspection can then be taken based on new estimates of remaining service life.

Implementation strategy

All background data discussed earlier to describe the base conditions of water mains can be conveniently implemented in a spreadsheet. This preliminary form of implementation

Fig. 6. "Multiple-time corrosion pit measurements" option methodology to estimate remaining service life of grey cast iron mains: (*a*) pipe segments, (*b*) 15th year inspection.



would capture the principal aspects of the analysis described by eqs. [2]–[9], [11], [13], and [14]. A more complete implementation would involve automatic data input on corrosion pits from NDE inspections. The illustrative examples were analysed using such an implementation.

Illustrative examples

Example 1: One-time pit measurement sensitivity analyses

In this example, grey cast iron water mains with diameters of 150 mm (6 in.) and 300 mm (12 in.) were analysed using the proposed methodology. The sensitivity analysis was carried out to illustrate the effect of initial measurements of corrosion pit depths on factors of safety and their influence on the remaining service life of water mains. Analyses were compared using both the Rossum and exponential corrosion models. The following steps were followed to conduct the sensitivity analysis:

(1) Data on pipe and soil characteristics and on operating conditions are presented in Table 2. Specific parameters used to describe corrosion models are shown in Table 3. It is not expected that water mains installed in the 1930s would have been designed to resist frost loads except by embedment below the lowest anticipated frost line. Therefore, the frost load factor is specified as zero for analysis in Step (2). Corrosion effects are only considered after Step (3).

(2) The safety factor was set to the recommended value of 2.5, and the pipe net thickness was determined by iteration (Fig. 4) so that the failure criteria (eqs. [1] or [10]) are satisfied. Step (2) is required in the design of new mains only where pipe diameter and wall thickness of an existing water main are provided as input.

(3) Initial pit dimensions (pit depth, width, and length) and frost load factor were specified. Although frost load was not considered in the original design, it cannot be inferred that it does not exist. The frost load was estimated to be 50% of the earth load. Either the Rossum or the exponential corrosion model was selected at this stage of the analysis. Step (3) is not required in the design of new mains.

(4) The sensitivity analysis was conducted by solving repeatedly for the factor of safety corresponding to a specified remaining service life (0, 25, 50, 100, 150, 200 years) using iteration so that the failure criteria are satisfied.

Figure 7 shows the decrease in factor of safety with time from which the utility can determine at what time each water main will fall below an acceptable factor of safety. The analysis shows that the factor of safety is lower for small pipes than for larger pipes at a given time even though the 150 mm (6 in.) pipe has the same initial corrosion as the 300 mm (12 in.) pipe. This outcome is in agreement with the fact that small diameter mains are likely to suffer breaks earlier than the larger diameter mains because of the significant influence of the corrosion pits size on the structural resistance of small diameters mains.

The proposed methodology can be used to identify the influence of initial pit depth and constant pit width and length on the remaining service life for grey cast iron mains of different sizes. As expected, the estimated remaining service life decreases with the increase of the initial pit depth. The remaining service life is again less for a small diameter pipe than for a large diameter pipe with the same initial pit dimensions.

Example 2: Multiple-time corrosion pit inspections

A grey cast iron water main with a diameter of 450 mm (18 in.) and initial wall thickness of 16 mm (0.64 in.) was analysed following the proposed methodology. Table 2 gives a complete description of the water main. The following assumptions were made:

- there is no likelihood of frost action at this particular water main location
- the grey cast iron main was initially designed with a factor of safety of 2.5
- operational conditions remain unchanged between the time the water main was installed and the time of second inspection
- the time interval between first and second corrosion pit inspections on this segment was 10 years

Pit depths, widths, and lengths found from first and second inspections are shown in Table 4. These values were randomly generated at four locations to illustrate the use of the multiple-time option. The specific functions used for two inspections were $k_{1st} = 0.1h + 0.15h$ random() and $k_{2nd} = k_{1st} + 0.1h$ random(), respectively, where h is the pipe wall thickness and k is the generalized variable to describe any pit dimension. Stress-states (w/W, p/P) of each corrosion pit in the grey cast iron pipe segment can then be determined at the time of each inspection as shown in Fig. 8. In this example, every pit is assigned an identification tag as noted in Ta-

Table 2. Characteristics of grey cast iron mains used in examples 1 and 2.

	Example 1		Example 2
Pit grey cast iron water mains	6 in.	12 in.	18 in.
Pipe nominal diameter	152.40 mm	304.80 mm	457.20 mm
Total thickness	9.28 mm	12.92 mm	16.36 mm
Pipe manufactured and placed	1930	1930	1930
Pipe age	67 yr	67 yr	67 yr
Backfill material	Sand	Sand	Sand
Native soil	Clay	Clay	Clay
Trench depth to crown of pipe	1.52 m	1.52 m	1.52 m
Backfill weight density	18.85 kN/m^3	18.85 kN/m^3	18.85 kN/m^3
Pipe laying condition	Type B	Type B	Type B
Load factor dependent on laying condition	1.45	1.45	1.45
Ratio of horizontal to vertical pressure coefficients	0.4	0.4	0.4
Coefficient of sliding friction (trench wall and backfill)	0.325	0.325	0.325
Working or operating pressure	1379 kPa	1379 kPa	1379 kPa
Surge pressure allowance	827 kPa	758 kPa	690 kPa
Water temperature in warm season	15°C	15°C	15°C
Water temperature in cold season	1°C	1°C	1°C
Frost load factor	0.5	0.5	0.5
Impact traffic factor	1.5	1.5	1.5
Wheel load	40.12 kN	40.12 kN	40.12 kN
Traffic reduction factor	1	1	0.9
Bursting tensile strength	124 MPa	124 MPa	124 MPa
Tensile strength	207 MPa	207 MPa	207 MPa
Ring rupture modulus	276 MPa	276 MPa	276 MPa
Fracture toughness	10 MPa·m	10 MPa·m	10 MPa·m
Toughness correction coefficient (*a*)	0.1	0.1	0.1
Toughness exponent (*s*)	1	1	1

Note: 1 MPa = 145 psi; 1 MPa√m = 0.92 ksi√in.

Table 3. Corrosion models used in example 1.

Rossum	$p = K_n\left[\frac{(10 - \mathrm{pH})t}{\rho_{\mathrm{soil}}}\right]^n = K_n z^n$
Soil pH	7.5
Soil resistivity	1500 Ω-cm
Pitting rate constant (K_n)	4.32
Pitting rate at 1st inspection	0.006 mm/yr
Aeration constant (*n*)	1/6
Exponential	$p = at + b(1 - e^{ct})$
Minimum pitting rate constant (*a*)	0.009 mm/yr
Constant related to maximum pitting rate (*b*)	6.27 mm
Reciprocal of time constant (*c*)	0.14 1/yr

ble 4 and Fig. 8. The first letter identifies the corrosion pit (b, c, d, and e for Case 1 (earth and truck) loading; v, w, x, and y for Case 2 (internal and surge pressures) loading) and the second letter represents the time of inspection (B(before) = first inspection and A(after) = second inspection). If the operational conditions do not change and the resistance capacity decreases as a consequence of the presence of the corrosion pits, then the stress-state for each pit will move toward the ultimate failure envelope as shown in Fig. 8.

The following steps were followed to evaluate the grey cast iron mains after the second inspection.

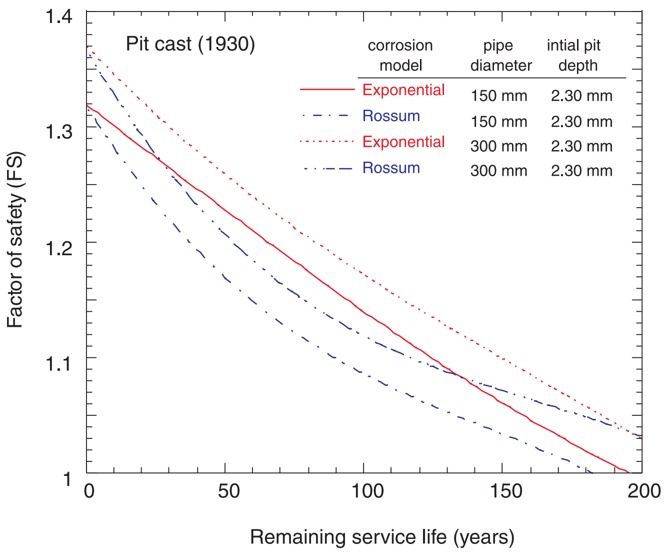
(1) Input data on pipe and soil characteristics and on operating conditions were used as summarized in Table 2.

Table 4. Hypothetical pit dimension measurements from non-destructive testing.

1st inspection					2nd inspection				
Pit id		Depth	Width	Length	Pit id		Depth	Width	Length
Case 1	Case 2	(mm)	(mm)	(mm)	Case 1	Case 2	(mm)	(mm)	(mm)
b-B	v-B	2.66	2.766	3.341	b-A	v-A	3.545	3.26	3.42
c-B	w-B	2.91	1.903	3.246	c-A	w-A	3.206	3.501	4.758
d-B	x-B	2.524	2.767	2.523	d-A	x-A	3.258	3.711	2.545
e-B	y-B	3.334	3.711	2.815	e-A	y-A	3.939	4.729	3.824

Note: 1 mm = 0.03937 in.

Fig. 7. Comparison of time dependent factors of safety for grey cast iron water mains of two pipe sizes — example 1.

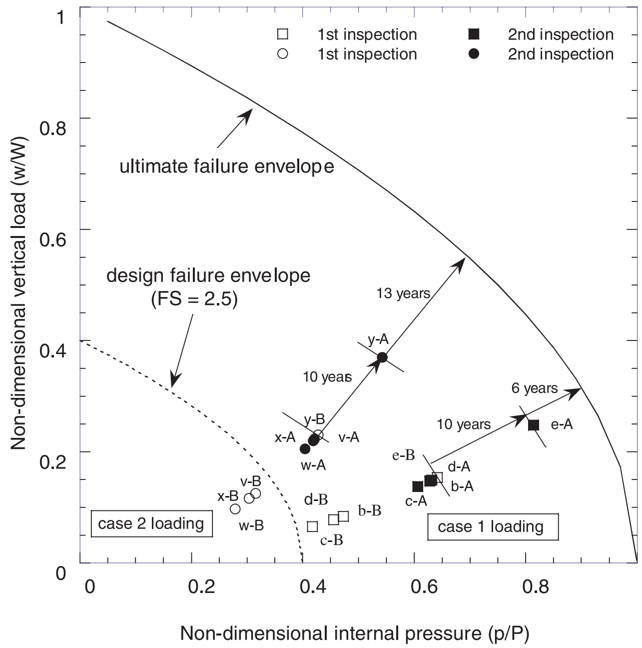


(2) The safety factor was set to the recommended value of 2.5, and the net thickness of pipe wall was determined by iteration to satisfy the failure criteria (eqs. [1] or [10]). Step (2) is required only in the design of new mains, whereas the pipe diameter and wall thickness of existing water mains are provided as input.

(3) Stress-states (w/W, p/P) were determined from pit dimensions (pit depth, width, and length) of each individual corrosion pit detected in the first inspection as shown by round (○) and square (□) "open" bullets for Case (1) and Case (2) loadings. The stress-states were then recalculated from the pit dimensions obtained from the second inspection as shown by round (●) and square (■) "filled" bullets for Case (1) and Case (2) loadings.

Figure 8 shows how the stress-states for each corrosion pit for load cases 1 and 2 moves towards the ultimate failure envelope over time. The remaining service life is estimated on a proportional basis from the time for the corrosion pit to migrate from the stress-state at first inspection to second inspection and how far it is from the ultimate failure envelope. This procedure assumes that the corrosion rate is constant, which is expected for pipes in advanced stages of corrosion. The worst corrosion pit is the one that produces a stress-state closest to the ultimate failure envelope (pit e-A in this example). The expected time (6 years) for this pit to reach the ultimate failure envelope is the estimate for the remaining service life for the pipe segment. The remaining service

Fig. 8. Application of "multiple-time corrosion pit measurements" option to estimate the impact of corrosion on grey cast iron mains — example 2: B = 1st inspection, A = 2nd inspection.



life for the same corrosion pit for load case 2 is 13 years. The multiple-time option presupposes that data on corrosion rate are not available.

Conclusions

A general methodology for estimating the remaining service life of grey cast iron water mains has been described. This methodology is dependent on measurements of dimensions of corrosion pits or on estimates of corrosion rates if a history of such measurements is not available. It is based on the type (pit or spun) of grey cast iron pipe and of the pipe loading, operational, and environmental conditions. This information, along with the mechanical properties of grey cast iron and relationships developed elsewhere between the residual tensile strength and specific dimensions of corrosion pits enables an estimation of the remaining service life of each segment in a water system.

The methodology requires the measurement of corrosion pit sizes. While this type of measurement can be performed directly during routine maintenance or as a result of a special research program, a more desirable procedure would be to measure the corrosion pit sizes using non-destructive evaluation technology. While one commercial application is currently available to measure pit depths, there is no doubt that it will take some time before three-dimensional measurements become a routine procedure for water utilities. Improvements in the three-dimensional visualization and characterization of these defects using NDT methods are required for the easy application of the methodology.

Estimates of corrosion rates are essential when the methodology to estimate remaining service life is applied for the first time. These estimates of corrosion rates are largely dependent on local environmental conditions and can vary with time. Consequently, it is recommended that water utilities institute routine procedures to estimate corrosion and corrosion rates as a part of their water main break repair or replacement activity. While it is not always feasible to take samples of grey cast iron mains during these activities, advantage should be taken of every opportunity that arises. An understanding of the corrosion behaviour of a water system can then easily be built over the course of several years.

It is also recommended that case studies be performed to validate the proposed methodology. These case studies will serve to identify the limitations of any of the individual building blocks of the methodology and to indicate its practicality.

The methodology is flexible enough so that future improvements to any of its individual components can easily be incorporated. New developments in the understanding of the behaviour of grey cast iron pipes, the effects of corrosion pits on their structural capacity, estimation of corrosion rates, and NDE technology should therefore be included in the methodology as they occur. In addition, a probabilistic extension of the methodology to deal with the uncertainties produced by variable corrosion rates, external loadings, and other parameters should be developed to enhance the usefulness of the methodology in making decisions about pipe repair and replacement.

Acknowledgements

The Institute for Research in Construction (IRC) of the National Research Council of Canada (NRC) gratefully acknowledges that the American Water Works Association Research Foundation (AwwaRF) is the joint owner of the technical information upon which this publication is based. The Institute for Research in Construction of the National Research Council of Canada thanks the Foundation for its financial, technical, and administrative assistance in funding and managing the project through which this information was discovered. Without the Foundation's support and encouragement, this publication would not be possible. The National Research Council of Canada is indebted to the water utilities (Edmonton, Moncton, Montreal, Quebec City, Regional Municipality of Ottawa-Carleton, Toronto, Vancouver, Winnipeg, Boston, Chicago, Denver, Minneapolis, Philadelphia, San Francisco, St. Louis County, and Washington Sanitary Suburban Commission) who provided pipe and soil samples that formed a basis for the proposed methodology to estimate remaining service life of grey cast iron mains. The comments and views detailed herein may not necessarily reflect the views of AwwaRF, its officers, directors, affiliates, or agents.

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List of symbols

a, b, c, and K_n constants in corrosion models
L pipe age – time elapsed between time of installation and inspection of water mains
a_n notch length
d/h pit depth-pipe wall thickness ratio
D pipe diameter
E_p pipe material secant elastic modulus
FS_{fail} designated minimum factor of safety
f_{frost} frost load multiple factor
k_{1st}, k_{2nd} specific functions used to generate pit depths for example 2
K_q "provisional" fracture toughness
n soil redox potential represented through a soil aeration constant
p pipe internal pressure
pH soil acidity/alkalinity
r_g, p_c corrosion pit dimensions at any time (t), i.e., pit depth (p_{depth}), width (p_θ), and length (p_x)
$r_{inspect}$ corrosion pit dimensions determined at inspection time $t_{inspect}$
random() random number generator used to generate pit depths for example 2
P internal pressure necessary to cause failure
h pipe wall thickness
$t_{FS_{fail}}$ time it takes to reach designated minimum factor of safety
$t_{residual}$ remaining service life
w ring load
W three-edge crushing (ring) load necessary to cause failure
α, s constants for fracture toughness equation
α_p linear thermal expansion coefficient of pipe material
β geometric factor for fracture toughness
ΔT maximum temperature difference between water temperature and surrounding soil
ν_p Poisson ratio for pipe material
ρ_{soil} soil resistivity
σ_θ hoop stress
σ_n nominal stress at failure
σ_r modulus of rupture
σ_x axial stress
σ_y tensile strength or uniaxial tensile strength