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Impact of Uncertainties on the Translation of Remaining Pipe Wall Thickness to Structural Capacity

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Abstract

Drinking water distribution systems form essential components of most urban centres. Water mains (or pipes) buried in the soil/backfill are exposed to different deleterious reactions and as a result, the design factor of safety may significantly degrade, leading to structural failure. In particular, metallic distribution and trunk mains are subject to corrosion. Proactive pipeline management, which entails timely maintenance, repair and renovation, can increase the pipe service life. Several non-destructive evaluation (NDE) techniques have recently become available to measure the remaining wall thickness of metallic pipes. In this paper, an analytical model based on Winkler-type pipe-soil interaction (WPSI) is used to translate the remaining pipe wall thickness to current structural factor of safety. The WPSI model takes into consideration external (traffic, frost, etc) and internal (operating and surge pressures) loads, temperature changes, and loss of bedding support as well as the reduction of pipe structural capacity in the presence of corrosion pits. Uncertainties in the input data/parameters are handled using possibility theory and fuzzy arithmetic. Sensitivity analysis is carried out to identify the critical data/parameters that merit further investigation.

Keywords: Jointed water mains, Winkler model, pipe-soil interaction, elasto-plastic soil.

Introduction

The deterioration of aging water mains (pipes) is of increasing concern to all stakeholders, namely, water utilities (owners) as well as their customers. Consequently, their ability to deliver safe potable water without major interruptions is paramount. It is estimated that the financial costs to water utilities (public or private owners) for their repair and replacement exceeds $1 billion annually in Canada alone. The implementation of a proactive asset management strategy is essential to maintain a water distribution system that is both reliable and safe, given the limited availability of financial resources. In the past few years, different non-destructive techniques (NDT) have become available (Hartman and Karlson 2002; Rajani and Kleiner 2004) to measure remaining wall thickness, corrosion pits (ductile iron) or graphitization depths (cast iron) along pipe lengths. Results obtained from these NDT measurements have to be incorporated within a broad decision support tool to assess condition state, determine remaining service life for each pipe that is inspected and subsequently establish proactive management strategies.

In most cases a combination of circumstances leads to the failure of any one particular water main. It is very difficult to ascertain the precise cause because all the operational factors or data, e.g., external (traffic, frost, etc.) and internal (operating and surge pressures) loads, temperature changes, loss of bedding support, pipe condition, and corrosion pit geometry, are not always known or recorded accurately, if at all. Any attempt to establish or estimate condition state has a degree of uncertainty given that many of the factors that contribute to pipe failure themselves have significant uncertainties either because of the large spatial variability, e.g. soils, (even in a moderate size networks) or inherent variabilities, e.g. pipe material properties. Uncertainties in the estimates of remaining service life are especially exacerbated given the difficulties associated with obtaining reasonable estimates of past, present and future corrosion rates. Rajani et al. (1996) and Rajani and Tesfamariam (2004) have developed a Winkler-type pipe-soil interaction (WPSI) model that accounts for most of the predominant factors or data/parameters identified earlier. This paper describes further development of this model to include failure theories specific to cast iron mains as well as to account for the remaining wall thickness or pit geometry measurement obtained from NDT inspections. This enhancement of the model should facilitate as well as explain the observed failure modes of cast iron mains.

Existing physical deterministic models for pipe-soil interaction provide point estimates (or fixed values) to determine a factor of safety (FS). This is generally not sufficient to identify predominant contributory factors that explain a specific failure mode that accounts for the uncertainties identified earlier. Therefore, the model needs to be further developed to include uncertainties in order that the “probability” or “possibility” of pipe failure can be quantified. Possible approaches for doing this are Monte Carlo simulations, first order reliability methods and possibilistic analysis using fuzzy arithmetic. In this paper, a possibilistic approach based on the fuzzy method is pursued to include uncertainties in operational factors and data. Sensitivity analysis using rank-correlation coefficients is carried out to identify and evaluate the contributions of critical factors /parameters to the factor of safety.

Pipe-soil interaction models

Rajani and Tesfamariam (2004) recently developed a Winkler-type pipe-soil interaction model that accounts for the unsupported length (likely to develop as a result of prolonged leakage or wash out) and soil elasto-plasticity on the axial and flexural responses. Further, the axial, flexural and circumferential stress components were consolidated with the previously reported (Rajani et al. 1996; Ugural and Fenster 1987) responses, to provide an overall picture of the response of buried water mains under the influence of earth and live loads, water pressure, temperature differential, unsupported length and pipe-soil interaction.

Only sufficient details on the WPSI models developed by Rajani et al. (1996) and Rajani and Tesfamariam (2004) are given here to explain the extension of the model to include failure analysis of cast iron mains. In general, the stress components due to external loads (σ_x^w), internal pressure ($\sigma_x^{p_i}$), temperature differential (σ_x^T) and longitudinal bending (σ_x^f) that contribute to the total axial stress (σ_x^a) are,

[1] $$\sigma_x^a = \sigma_x^w + \sigma_x^{P_i} + \sigma_x^T + \sigma_x^f$$

Similarly, the total hoop stress (σ_θ^{Total}) has contributions from external loads (σ_θ^w), internal pressure ($\sigma_\theta^{p_i}$), temperature differential (σ_θ^T) and longitudinal bending (σ_θ^f),

[2] $$\sigma_\theta^{Total} = \sigma_\theta^w + \sigma_\theta^{P_i} + \sigma_\theta^T + \sigma_\theta^f = \sigma_\theta^w + \sigma_\theta^{P_i} + \sigma_\theta^T - \nu_p \sigma_x^f$$

where ν_p is the Poisson's ratio. The thermal axial (σ_x^T) and hoop (σ_θ^T) stresses in [1] and [2] are a consequence of temperature differential (ΔT) between the inside of the pipe and the surrounding soil. Each of the stress components in [1] and [2] can be estimated using the solutions provided in the above-cited references.

Failure theories

In-plane failure criterion for cast iron

Water mains or pipes in service are subjected to continuous deleterious reaction(s) and internal and external loads that undermine the intended design factor of safety (FS). Consequently, the service life is significantly reduced due to the diminished structural resistance and exceeds the expected or admissible design loads or stresses. Pipe failure is defined as an event if the factor of safety falls below 1, i.e., FS < 1. Cast iron, a brittle material, typically fails through facture at strains of 0.5%, rather than through yielding. Thus failure of brittle materials such as cast iron is dictated by ultimate strength, whereas in contrast, yield strength is used to describe failure of ductile materials like ductile iron mains. Several theories (Ugural and Fenster 1987) exist to express the failure of cast iron materials but the most common theory used for the design of cast iron mains (AWWA C101-67 1977) is based on interaction curves developed by Schlick (1940). The AWWA C101-67 (1977) design guidelines treat cast iron pipes as a rigid structural ring element, and as a result, loads are supported by resistance in the in-plane direction and not in longitudinal bending, since a new well constructed pipe is not expected to undergo differential lateral movement/displacement (along the length of the pipe). Experimental work carried out by Schlick (1940) showed that the failure of a grey CI pipe is governed by parabolic interaction curves of internal pressure, *p*, and external bearing load, *w*.

$$\left(\frac{w}{W}\right)^2 + \frac{p}{P} \leq 1 \qquad [3]$$

where W and $P\ (= 2\sigma_u t / D)$ are the ultimate ring and burst loads, respectively; *t* is the thickness of the pipe (mm); *D* is the diameter of the pipe (mm); and σ_u is the ultimate cast iron strength in tension. The external load, *w*, in the C101-67 (1977) design guidelines considers traffic and overburden loads. However, additional frost loads induced during cold seasons in frost susceptible soils/backfills are not explicitly considered. Rajani and Makar (2000) suggest that frost load could be estimated as a multiple ranging from 0 to 1 of the earth load in accordance with the frost load theory developed by Rajani and Zhan (1996). AWWA C101-67 (1977) advocates the application of a "factor of safety" of 2.5 to internal pressure (*p*) and external loads (*w*) for the design of cast iron pipes. In today's terminology in structural design, the term "factor of safety" would be referred to as "load factor" since the design is based on limit states. It makes no difference which term is used in the design procedure as suggested by AWWA C101-67 (1977), since the same "factor of safety" of 2.5 is advocated for both internal pressure (*p*) and external loads (*w*). An additional pipe wall thickness of 2.03 mm (0.08") is suggested for corrosion (graphitization) allowance, which should increase the FS to values beyond suggested for structural resistance only. Nevertheless, as corrosion or graphitization pits initiate randomly and subsequently grow over time, the structural FS of a pipe diminishes (Rajani and Makar 2000; Rajani and Tesfamariam 2004) until failure, even though external and internal loads may not have changed significantly.

The in-plane failure criterion, [3], can be re-written in terms of the factor of safety, FS_{ip}, as follows:

$$FS_{ip}^2\left(\frac{w'}{W}\right)^2 + FS_{ip}\left(\frac{p'}{P}\right) = 1 \qquad [4]$$

where w' and p' are working loads and pressures, respectively. Failure is assumed to be imminent if $FS_{ip} < 1$.

Bi-axial distortion energy failure criterion for cast iron

The in-plane failure criterion incorporates only the ring (hoop) stress component. However, pipes in service are subjected to cyclic temperature variations and loss of bedding which in turn induce bending and subsequently axial stress. The development of cast iron fracture criteria under bi-axial (hoop and axial) stresses dates back to the 1950's (Coffin 1950; Fischer 1952; Mair 1968). These researchers investigated the response of cast iron in the presence of graphite flakes. Typically, the ferrite-graphite matrix transmits the load when the cast iron is in compression, however, the graphite flakes act as stress raisers when it is subjected to tension. This has the consequence that the ultimate tensile strength for cast iron stress is substantially lower than the ultimate compressive strength. Mair (1968), based on his experimental work and that of Coffin (1950) and Fischer (1952), arrived at the conclusion that the cast iron failure criterion is best represented by distortion energy theory developed by von Mises. This theory states that, failure by yielding or fracture occurs when, at any point in the body, the distortion energy per unit volume in a state of combined stress becomes equal to that associated with yielding or fracture in a simple tension test (Ugural and Fenster 1987).

The bi-axial failure criterion based on distortion energy theory is:

[5] $$(K\sigma_1)^2 - K\sigma_1\sigma_2 + \sigma_2^2 = \sigma_u^2$$

where K is a stress concentration factor (K= 3 for $\sigma_i (i = 1, 2)$) in tension; K = 1 for $\sigma_i (i = 1, 2)$ in compression), σ_i are the principal (σ_x^a and σ_θ^{Total}) stresses. The stress concentration factor, K, discussed here should not be confused with that typically used to calculate stresses in the presence of defects with specific geometry, although it has the same connotation since the stress concentration factor discussed here represents an aggregate reduction in tensile strength in the presence of carbon flakes which act as stress raisers. The distortion energy failure criterion for bi-axial stresses, [5], can be re-written in terms of the factor of safety, FS_{de}, as follows:

[6] $$\begin{aligned} K\sigma_i &= \sigma_u / FS_{de} && \text{for } \sigma_1 \textit{ and } \sigma_2 > 0 \text{ (tension)} \\ (K\sigma_1)^2 - K\sigma_1\sigma_2 + \sigma_2^2 &= (\sigma_u / FS_{de})^2 && \text{for } \sigma_1 \textit{ or } \sigma_2 < 0 \text{ (compression)} \end{aligned}$$

Residual ultimate strength

The ultimate strength of cast iron referred to in [3] and [5] is pertinent to cast iron that has no defects or corrosion (or graphitization) pits. The size of corrosion pits diminishes the intrinsic material strength of cast iron to the so-called residual ultimate strength (σ_{ur}) in accordance with fracture mechanics theory (Rajani et al. 2000) as follows,

[7] $$\sigma_{ur} = \frac{\alpha K_q}{\beta \left(d / t_{res} \sqrt{a_n}\right)^s}$$

where α and s are constants used in the fracture toughness equations; K_q is provisional fracture toughness; d is corrosion pit depth (mm); t_{res} is remaining wall thickness, ($t - d$), (mm); a_n is lateral dimension of a pit = Ld (multiplier L can be judged to have a value in the range of 1-5 in the absence of data); β is the geometric factor for a double-edged notched tensile specimen, $\beta = a_1 \left(d / t_{res}\right)^{b_1}$, and a_1 and b_1 are constants for determining the geometric factor. Rajani et al. (2000) established fracture toughness and other related parameters (K_q, b, a_1, b_1) based on limited experimental tests conducted on cast iron specimens taken from pipe samples.

Uncertainty analysis

Complex models often involve input data or parameters with uncertainties, which are best represented by random variables with known or assumed probability distributions or ranges of values based on experience and engineering judgement (Ross 2004). These uncertainties can be grouped under two major classes. The first class is the model uncertainty, which includes the model formulation as well as model coefficients. This uncertainty is the result of the abstraction (oversimplification) of natural processes. The second class includes uncertainty in input data, which can be broadly classified into two main types of uncertainties. Type I uncertainty (variability) arises as a result of heterogeneity or stochasticity, and such uncertainty cannot be controlled. Type II uncertainty is due to partial ignorance resulting from systematic measurement error or subjective (epistemic) uncertainty. It is postulated in this paper that epistemic uncertainty (incomplete knowledge and/or lack of data) dominates the decision analysis of the problem at hand. Type II uncertainty can be reduced by collecting more information and data. It plays an important role when the evidence base is small (i.e., data sparse situation) e.g., in our context, the assessment of the factor of safety of buried pipes operating in poorly characterized environments. It is vital to analyze these uncertainties due to the high-consequences associated with the failures of major water supply lines (Ferson and Ginzburg, 1996; Ferson et al., 2004).

Different uncertainty analysis techniques have been used to study reliability of cast iron pipes. Ahmed and Melchers (1994) used the first order reliability method to incorporate uncertainties in the input parameters. Sadiq et al. (2004) used the Monte Carlo (MC) simulations to develop a hazard function of time to failure. Both methods rely on either prior belief or knowledge of the statistical distributions of the input parameters. Acquisitions of these rigorous statistical distributions are not always possible for most buried pipe infrastructure. As a result, one has to resort to assumptions based on subjective knowledge.

In this paper, fuzzy set theory is used to represent uncertainties, since the theory is able to deal effectively with epistemic uncertainties that encompass vagueness and allows approximate reasoning as well as the intrinsic ability of the theory to propagate the uncertainties through the model. Fuzzy-based techniques are a generalized form of interval analysis used to address uncertain and/or imprecise information. Fuzzy numbers qualify as fuzzy sets if they are normal, convex and bounded (Klir and Yuan (1995) give definitions for these terminologies).

The use of fuzzy-based techniques obviates the requirement to make assumptions about type of the distribution (as required in MC simulations). In cases where some input data or parameters are supported by statistical evidence to establish probability density functions, these functions can be combined with fuzzy numbers to form a hybrid approach (Guyonnet et al., 2003).

A fuzzy number describes the relationship between an uncertain quantity x and a membership function μ_x, which ranges between 0 and 1. A fuzzy set is an extension of the classical set theory (in which x is either a member of set A or not) in that an x can be a member of set A with a certain degree of membership μ_x. In this work, in order to simplify the implementation, triangular fuzzy numbers (TFNs) are selected, however, although any fuzzy number shape is possible, the selected shape should be justified by available information (Guyonnet et al., 1999).

Fuzzy subsets (or fuzzy numbers), such as TFNs are often interpreted as *possibility distributions* (in contrast to probability distribution) (Klir and Yuan, 1995). Zadeh (1978) was the first to propose a *theory of possibility* based on fuzzy sets. Within the framework of quantitative possibility theory, the term *possibility*, denoted by π is understood in terms of plausibility (a terminology referred in Dempster-Shafer theory, Alim (1988)). A possibility distribution represents a state of knowledge about an issue, distinguishes between what is plausible and what is less plausible, and between what is surprising and what is expected (Dubois and Prade, 1998). Possibility theory defines an additional measure called *necessity*, denoted by N (an equivalent terminology is "belief" referred in Dempster-Shafer theory, Alim (1988)). The necessity (certainty or surety) of an event A is expressed as $N(A)$. If $N(A) = 1$, then the event A is necessarily true (or sure to happen). If A^c denotes the complement of event A then possibility theory requires (Dubois and Prade, 1998; 2001) that

[8] $$\pi(A) = 1 - N(A^c)$$

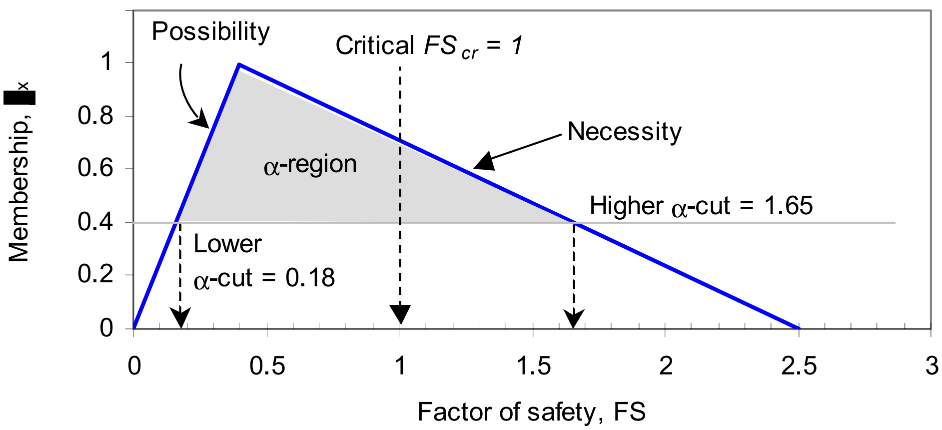
If x represents an arbitrary variable, say, factor of safety, from a universe of discourse U of factor of safety (Fig. 1), and u is an arbitrary value $u \subseteq U$ and A denotes an event in which $x > u$, then A^c denotes the event in which $x \leq u$, i.e.,

[9] $$\pi(x > u) = 1 - N(x \leq u) \quad u \subseteq U$$

Fig. 1 illustrates the *possibility distribution* implied by the above equation, where x represents the modeled factor of safety and u represents the "critical" factor of safety. The α-level cut on a fuzzy set, A_i, denoted by A_i^{α} is the subset of A_i consisting of all the elements in x (*support*) for which $\mu_{A_i}(x) \geq \alpha$. Fig. 1 illustrates the α-level cut concept (at $\alpha = 0.4$), where the subset $A_i^{0.4}$ represents the interval of FS from 0.18 to 1.65. At the lower level of $\alpha = 0.4$ (i.e., $FS = 0.18$), the possibility $\pi = 0.4$ and necessity $N = 0$, whereas at higher value of $\alpha = 0.4$ (i.e., $FS = 1.65$), the possibility $\pi = 1$ and necessity $N = 0.6$. It can also be interpreted that at $FS = 1.65$, the true probability of failure is between 0.6 (necessity N) and 1 (possibility π).

A safe structure should have critical factor of safety greater than unity, i.e., $FS_{cr} = FS \geq 1$. Thus, in reference to Fig. 1, there exists 30% necessity N (surety) and 100% possibility, π, that $FS < FS_{cr}$ (= 1).

Fig. 1 .   Possibility distribution for factor of safety and α-cut concept.



Integration of uncertainty analysis with pipe-soil interaction models and failure theories

The data/parameters required for the pipe-soil interaction models discussed in the previous section can be group into 3 broad categories: pipe (size and material properties), soil (trench characteristics and soil properties) and operational (operating pressure, unsupported length, etc). The uncertainties in each of these data/parameters are expressed (Table 1, Fig. 2) in terms of triangular fuzzy numbers TFNs (lower and upper bounds and most likely values) for a typical buried 200 mm (8") cast iron main. The uncertainties expressed for each data/parameter are based on the authors' best judgment and experience. "Crisp" values are used for properties known with certainty.

The solutions for each of the stress components [1]and [2] as well as the failure theories criteria were re-written in terms using fuzzy arithmetic to obtain realistic factors of safety, which is fuzzy in nature. The schematic flow chart used to the compute fuzzy factors of safety is shown in Fig. 2. The major advantage to determine fuzzy factors of safety is uncertainties present in the input data/parameters are reflected systematically in the final fuzzy factor of safety. Thus, increase or reduction in the uncertainty of any single input data/parameters is immediately reflected in the factor of safety.

Fig. 3. shows 4 distinct scenarios of how a change in the fuzzy factor of safety decreases with the increase in unsupported bedding length and corrosion pit depth and includes uncertainties as expressed in Table 1. The factor of safety decreases dramatically as the remaining wall thickness decreases. The situation (scenario with remaining wall thickness equal to 50% of original thickness) is exacerbated when the mains experience loss of bedding support (scenario with unsupported length of 0.5 m), which is likely to happen if the leak does not surface or goes undetected. The necessity (surety) measure for each fuzzy factor of safety increases as the deterioration increases as shown in Fig. 3.

Table 1 Input parameters for pipe, soil and operational conditions for 200 mm diameter cast iron mains.

	Lower bound	**Most likely**	**Upper bound**
Nominal diameter, D		203 mm	
Wall thickness, t		11.18 mm	
Pipe length, $2L$		6.0 m	
Elastic modulus, E_p	196000 MPa	206000 MPa	216000 MPa
Ultimate tensile strength	132 MPa	207 MPa	282 MPa
Ring modulus of rupture	235 MPa	310 MPa	385 MPa
Bursting tensile strength	94.8 MPa	145 MPa	195 MPa
Poisson's ratio, ν_p	0.24	0.26	0.28
Fracture toughness, K_q	7 MPa $\sqrt{m}$	10 MPa $\sqrt{m}$	13 MPa $\sqrt{m}$
Thermal coefficient, α_t		10.5E-06/^{o}C	
Elastic modulus, E_S	90 MPa	100 MPa	110 MPa
Poisson's ratio, ν_S	0.25	0.30	0.35
Soil unit weight, γ	22488 N/m^3	22988 N/m^3	23488 N/m^3
Trench depth, H	1.47 m	1.52 m	1.57 m
Trench width, B_d	0.71 m	0.81 m	0.91 m
Unsupported length, b	0	203 mm	406 mm
Earth load and traffic load, q	25.3 N/mm	34.3 N/mm	45.8 N/mm
Water pressure, P_i	172 kPa	345 kPa	689 kPa
Temperature difference	6^{o}C	-14^{o}C	-34^{o}C

Fig. 2 The computation of fuzzy factors of safety.

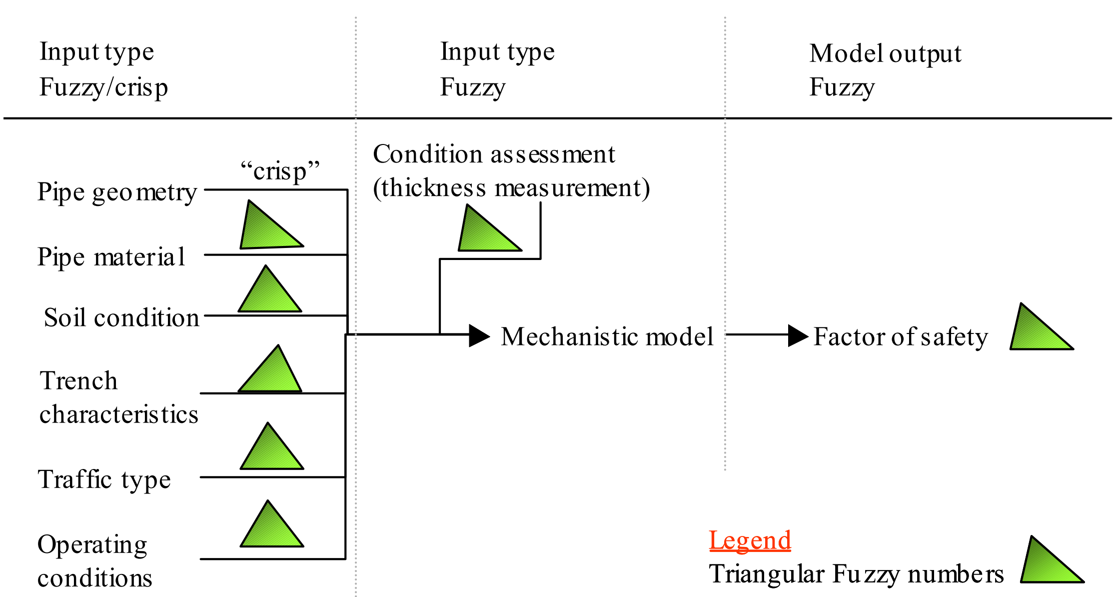
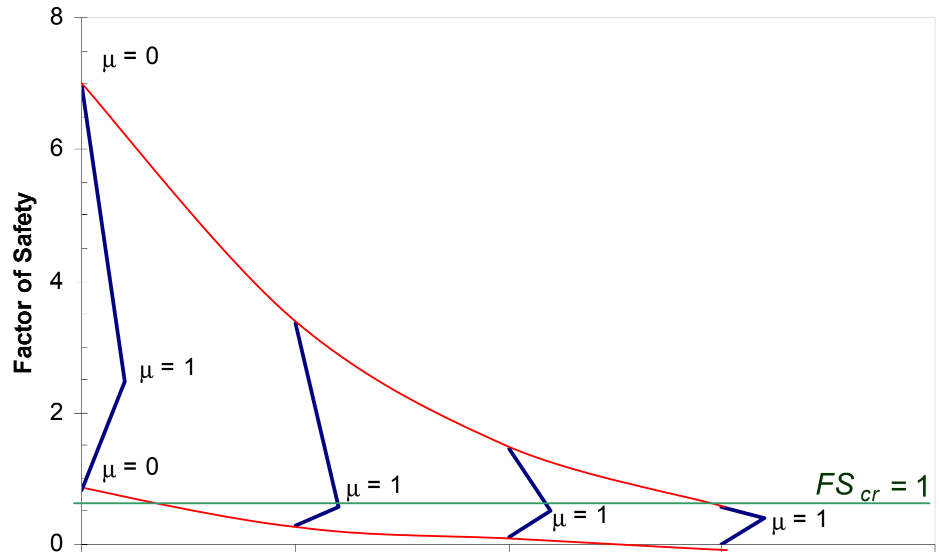


Fig. 3 Variation of fuzzy factor of safety with remaining wall thickness and increasing unsupported length.



Wall thickness, t	**t**	**75%t**	**50%t**	**50%t**
unsupported lenth, b (m)	**0**	**0**	**0**	**0.5**
Possibility, π	**0.01**	**1**	**1**	**1**
Necessity, *N*	**0**	**0.16**	**0.51**	**1**

Sensitivity analysis

Sensitivity analysis enables the identification of critical input data/parameters (ASTM 1998) that have a significant impact on the output results. Sensitivity analysis also serves as an aid to identifying the important uncertainties for the purpose of prioritizing additional data collection or research areas. It can also reveal which parameters can be de-emphasized or perhaps eliminated altogether without having a major impact on responses predicted by the model.

Several methods to conduct sensitivity analysis are available, each with associated advantages and disadvantages Cullen and Frey (1999). The most appropriate method deemed applicable for the uncertainties in the pipe-soil interaction and failure theories is the rank correlation method (Cullen and Frey, 1999; Hammonds, 1994; Maxwell and Kastenberg, 1994; Sadiq, 2001). Correlation coefficients are measures of the strength of the linear association between two variables. In statistics, procedures can be either parametric which invariably require normal distributions or nonparametric where assumptions about the distributions of variables are not essential. The parametric correlation (Pearson Product-Moment correlation coefficient, r) quantifies the relationship between the variables in the raw or transformed metric, i.e., it measures the extent of linearity of a relationship between two random variables. The nonparametric correlation (Spearman's rank correlation coefficient, r_s) measures the strength of the relationship of the ranks of the data, i.e., it measures the extent of monotonicity of a relationship between two random variables. The rank correlation coefficient (r_s) between two sets of variables is obtained from the summation of the difference of ranks (d_r) squared, i.e., $r_x = 1 - 6\Sigma d_r^2 / n^2(n-1)$ where n is the number of ranked values/items. The Spearman rank correlation coefficient is applied to the sensitivity analyses conducted here since the model is non-linear and while the input data may have normal distributions, this condition cannot be guaranteed for output (factor of safety) results.

The procedure for the sensitivity analysis based on the rank correlation method is applied in the context of fuzzy input data generated randomly (1000 realisations) using the α-cut concept of fuzzy sets. The α-cut can be used to form a fuzzy confidence band, which can be viewed as a possibilistic confidence interval analogous to the probabilistic confidence interval. The possibilistic confidence interval $A_i^{0.4}$ for the fuzzy factor of safety is [0.18, 1.65] shown in Fig. 1 as described before.

The procedure to generate random fuzzy factors of safety using fuzzy input data/parameters is the following:

For i = 1, N *where* ***N*** *is the number of simulations in the sensitivity analysis*

  For *each input,* ***j****,* $x_{i,j}$

    randomly generate , $a_{i,j}$*-level (uniformly distributed)*

    compute average (lower $x_{i,j}$ *at* $\mu = a_{i,j}$*, upper* $x_{i,j}$ *at* $\mu = (1 - a_{i,j})$*)*

  next j

    determine fuzzy stresses based on the fuzzy input(fi) using the pipe-soil interaction models

    determine total current fuzzy axial ($\sigma_x^a(i)$*) and hoop (*$\sigma_\theta^{Total}(i)$*) stresses as indicated in eqns. [1] and [2]*

    compute combinations of axial and hoop stresses that represent extreme and most likely stress conditions

    if *failure criterion = "in-plane failure"* ***then***

      compute fuzzy factor of safety from fuzzy hoop stresses

    if *failure criterion = "distortion failure"* ***then***

      compute fuzzy factor of safety from fuzzy axial and hoop stresses

next *i*

The Spearman rank correlation procedure was applied to the results obtained from the sensitivity analysis procedure outlined above. The normalized rank correlations are shown in the tornado graphs Fig. 4 and Fig. 5 for in-plane failure criterion for cast iron mains where the remaining wall thickness are 70% and 45%, respectively. Fig. 6 and Fig. 7 show similar normalized rank correlations for distortion failure criterion for remaining wall thickness are 70% and 45%, respectively.

Fig. 4 . Sensitivity of factor of safety to input variables for in-plane failure criterion and remaining wall thickness of 70%.

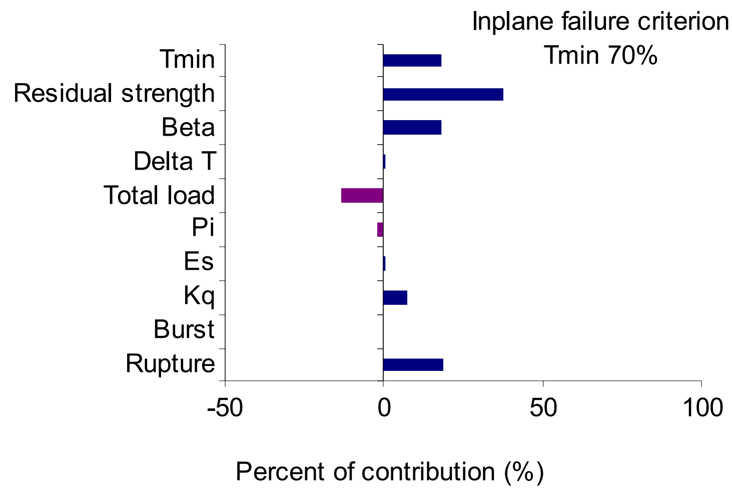
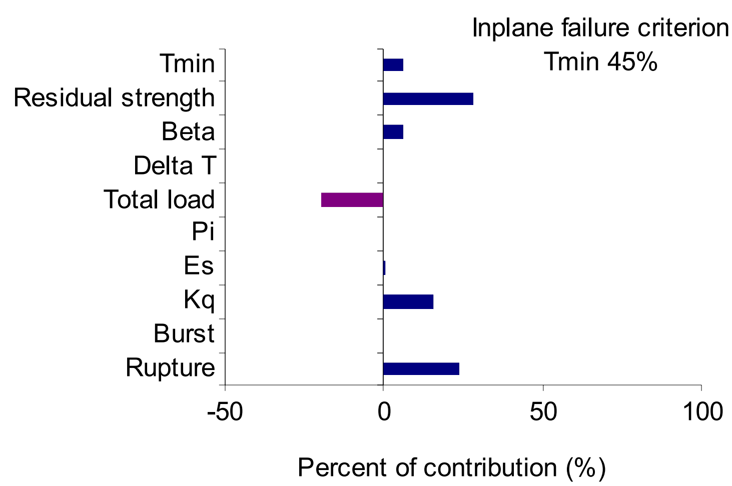


Fig. 5 . Sensitivity of factor of safety to input variables for in-plane failure criterion and remaining wall thickness of 45%.



Conclusions

A previously developed pipe-soil interaction model was combined with failure theories to determine the fuzzy factor of safety with uncertainties represented in input data as triangular fuzzy numbers. Fuzzification of the mechanistic pipe-soil interaction model combined with possibility theory provides a systematic manner to incorporate and propagate uncertainties at all levels throughout the solution process. The possibility analysis also allows the designer/owner/operator to decide the level of risk that s\he is willing to take and thus define different repair and maintenance strategies at different risk tolerances.

Fig. 6 . Sensitivity of factor of safety to input variables for distortion failure criterion and remaining wall thickness of 70%.

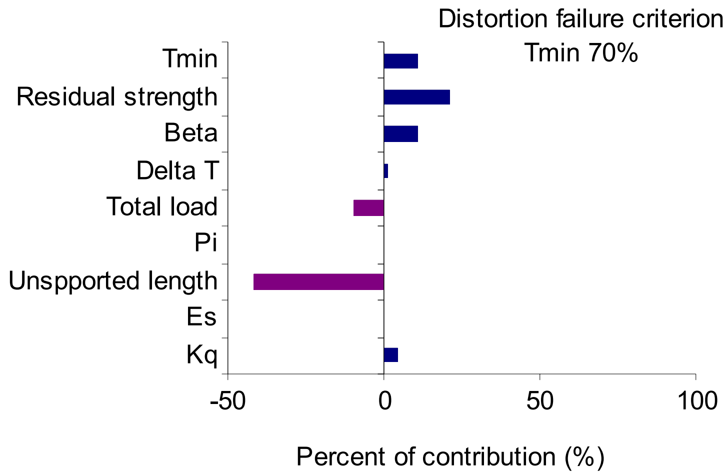
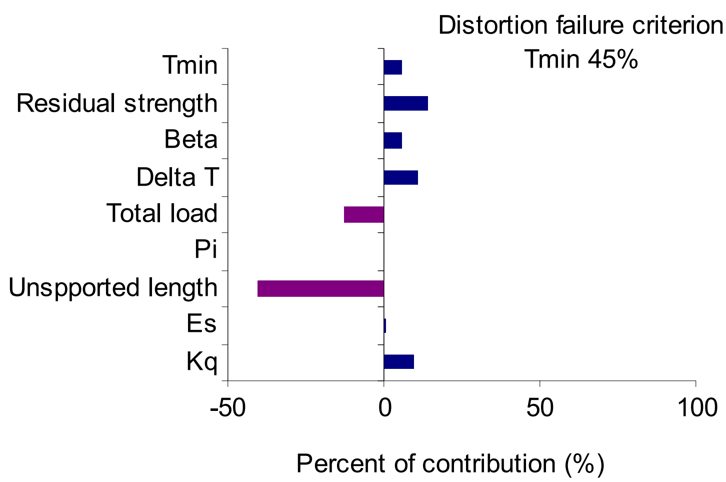


Fig. 7 . Sensitivity of factor of safety to input variables for distortion failure criterion and remaining wall thickness of 45%.



The sensitivity analysis clearly shows that some input variables such as increase in remaining wall thickness (or decrease in pit depth) and increase in the residual strength (biaxial) and increase in tensile strength (in-plane) have a positive impact on the factor of safety, independent of the failure criteria. Similarly, unsupported length, temperature differential and external load (including the effect of frost load) significantly reduce the distortion factor of safety. This situation is exacerbated at lower levels of remaining wall thickness (cf. Fig. 4 Fig. 5 for in-plane failure criterion and Fig. 6 and Fig. 7 for distortion failure criterion). These sensitivity analyses strongly suggest that reducing pit depth (graphitization) growth by using effective corrosion control can be an effective way to decelerate breakage growth rate. This observation corroborates the experience of utilities and corrosion engineers.

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