Translation of pipe inspection results into condition ratings using the fuzzy synthetic evaluation technique

Balvant Rajani, Yehuda Kleiner and Rehan Sadiq

ABSTRACT

An important step towards the assessment and management of failure risk in large-diameter (transmission) water mains is to observe distress indicators through scheduled inspections (using non-destructive or visual techniques) and translate these into condition ratings. Condition rating reflects an aggregate state of the pipe's health.

Distress indicators are physical manifestations of the ageing process. The type (or form) and location of observed distress indicators in large-diameter mains are dependent on the pipe material and its surrounding environment. The physicochemical processes that promote ageing are often not understood well enough to merit an adequate physicochemical (based on mechanics or electrochemistry or microbiology) model. Further, the encoding of distress indicators into condition rating is inherently imprecise and involves subjective judgement. Fuzzy logic-based tools enable the use of engineering judgement, experience and scarce field data to translate the level of distress to condition ratings.

This paper describes the translation of distress indicators detected by non-destructive or visual techniques into fuzzy condition ratings. Examples of distresses observed in prestressed cylinder concrete pipes (PCCP) and cast iron pipes are used to illustrate the proposed method.

Key words | distress indicator, fuzzy condition ratings, large-diameter transmission mains

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INTRODUCTION

The principal pipe materials used for the construction of large-diameter water transmission mains are steel, cast iron (CI), ductile iron (DI), reinforced concrete (RC), pre-stressed concrete cylinder pipe (PCCP), and asbestos cement (AC). Polyvinyl chloride (PVC) and polyethylene (PE) pipes have come into use more recently, especially in the lower diameter range. It is not unusual for these transmission mains to extend several kilometres or miles through terrain with varying soil characteristics. Typically, these pipelines consist of individual segments or units that are 6.1 m (20 ft) long but the pipe segments are usually of shorter length in the higher diameter (>900 mm or 36″) range.

Most water utilities in North America have not conducted routine inspections and condition assessments of their large-diameter water transmission mains (many utilities have not inspected their transmission mains even once). Typically, inspection is triggered ad-hoc, following a catastrophic failure or opportunistically when a pipe is taken off-line for repair.

Currently, all pipe inspection techniques that are commercially available for large water mains (including visual and NDT-based (non-destructive techniques)) require that the inspected pipe be drained. Large-diameter water transmission mains are an expensive component of the water supply system, and therefore the system often does not have enough built-in redundancy, i.e. ability to deliver water while these pipes are off-line. This is the main reason why water utilities are reluctant to inspect these pipes. The cost of the large amounts of treated water lost on

doi: 10.2166/aqua.2005.069

pipe drainage, as well as possible difficulties in disposing of this water are further reasons for the low rate of inspection. The condition of large-diameter water transmission mains is of little concern at an early age since a well-designed pipe would have an adequate built-in margin of safety. However, it is expected that failure rates may increase significantly as the pipes age and margins of safety diminish.

Jackson *et al.* (1992), Dorn *et al.* (1996), Makar and Chagnon (1999) and recently Dingus *et al.* (2002) have reported comprehensive reviews of pipe inspection methods. However, most of the reviewed inspection methods are specific to small-diameter mains. Mergelas and Kong (2001) and Elliott *et al.* (2002) described the development and application of a technique based on remote field eddy current/transformer coupling (RFEC/TC) that is applicable to large-diameter PCCP pipes. It detects the presence of broken wires and estimates their number.

In this paper the term 'inspection' refers to all methods of observing distress indicators, including visual and various NDT methods. Technologies behind specific inspection methods are not discussed since sufficient information can be obtained from cited references. In addition, specific reference is made to PCCP and cast iron mains because these pipe materials make up a large proportion of installed large-diameter pipelines and much experience and engineering judgement have been gained over the past years.

The condition assessment of a buried infrastructure asset is a costly procedure, and can be viewed as consisting of two distinct components. The first component involves the inspection of the asset using direct observations (visual, video) and/or non-destructive evaluation (NDE) techniques (radar, sonar, ultrasound, sound emissions, eddy currents, etc.). Inspection of an asset yields quantification and location(s) of distress: e.g. 2 mm wide crack at spring level located 2 m from the pipe bell, or 19 broken wires located 4 m from the spigot. The second component of condition assessment is the translation of these distress indicators into an overall condition rating of the asset. In this paper, the terms *observed distress indicator(s)*, *distress indicator(s)* and *observation(s)* are used interchangeably. Thus, a condition rating reflects the combined result of all observed distress indicators for one pipe segment.

Kleiner *et al.* (2006) described an approach to model the deterioration of buried infrastructure assets using a fuzzy rule-based, non-homogeneous Markov process. The fuzzy Markov deterioration model requires at least one condition rating of the pipe at a time that is sufficiently later than the time of installation, so as to produce observable distress indicators. This paper describes the process of how distress indicators are translated to the condition rating of the asset, using the fuzzy synthetic evaluation technique (FSE), which is one of several techniques used for fuzzy multi-criteria decision-making (FMCDM).

PROPOSED METHODOLOGY

Klir and Yuan (1995) classify uncertainty into forms of fuzziness (vagueness) and ambiguity (non-specificity and conflict). Fuzziness is usually identified with a lack of sharp distinctions; other synonyms of the word fuzzy include: blurred, indistinct, unclear, vague, ill-defined, out of focus, not clear, shadowy, dim, obscure, misty, hazy, murky, foggy and confused (Rocha 1997). Fuzzy sets (Zadeh 1996) are usually used to formalize this kind of uncertainty. On the other hand, ambiguity is identified when several alternatives exist for the same question or proposition. Evidential reasoning (Dempster 1967; Shafer 1976) provides an ideal framework for studying ambiguity: i.e. incomplete, non-specific, conflicting, and partially ignorant or missing information. This paper focuses mainly on the fuzziness type of uncertainty.

The fuzzy synthetic evaluation technique, which is a method based on fuzzy set theory, is employed here to translate observations to condition ratings. Recently, Yan and Vairavamoorthy (2003) adopted a similar approach based on *fuzzy composite programming* to rank pipes in a water distribution network according to their condition ratings. The term *synthetic* is used to connote the process of evaluation, whereby several individual elements or components of an evaluation are synthesized into an aggregate form. The underlying fuzzy approach can accommodate both numeric and/or non-numeric (e.g. linguistic) components. Simple fuzzy classification, fuzzy similarity method and the fuzzy comprehensive assessment, are all derivatives of fuzzy synthetic evaluation that have been used recently by a number of researchers (Tao and Xinmiao

1998; Lu *et al.* 1999; Chang *et al.* 2001; Lu and Lo 2002; Sadiq and Rodriguez 2004).

A typical fuzzy synthetic evaluation is a FMCDM technique that follows a distinct three-step process, namely, *fuzzification*, *aggregation* and *defuzzification* (Lu *et al.* 1999; Sadiq *et al.* 2004). Next, the general framework to establish perceived condition ratings is described, followed by a discussion and demonstration of how the framework is applied to prestressed cylinder concrete pipe, and cast and ductile iron pipe.

TRANSLATION OF PIPE INFORMATION TO DETERIORATION RATES

Factors that determine the long-term behaviour and performance of pipes include their intrinsic properties (material type, size, etc.) their operating conditions (pressure, water quality, etc.) as well as their external environment (soil, dynamic loading, etc.). As discussed earlier, distress indicators obtained from NDE (visual or otherwise) inspections reflect the current pipe condition, including the wear and tear that the pipe experienced up until the inspection. The FSE process described here encodes distress indicators into a condition rating using data/observations that are inherently imprecise, qualitative and often involve subjective judgement.

The factors that contribute to pipe deterioration are organized in a two-level hierarchical structure. Level 1 consists of categories, while level 2 comprises actual distress indicators. Each category aggregates one or more distress indicators. A category reflects a specific pipe component: e.g. prestressed wires in PCCP or the external coating of ductile iron pipe. A distress indicator reflects the wear and tear, and is a measurable or an estimable entity.

It is important to note that environmental or operational conditions or mechanisms that lead to pipe deterioration (ageing) are not explicitly considered to determine its condition rating. It is posited that the observable/measurable distress indicators are a *testament* to the combined impact of *all* the stresses (operational, environmental) that ever acted on the pipe. In other words, any adverse impact on the pipe such as corrosion or cracking will manifest itself in some form of observable distress and would be detected in the inspection. The following are two specific examples to illustrate this issue. (a) Some PCCP pipes, manufactured by Interpace with class III or IV prestressing wires between the late 1960 s and the mid-1980 s in accordance with AWWA C301–79 (1979) and prior standards, have been subject to hydrogen embrittlement. Thus, the fact that a pipe was made with a certain class of wire or is of a certain age has no relevance to whether a pipe has or does not have observable distress. (b) It is well accepted that in a corrosive environment, a cathodically protected pipe may deteriorate much slower than one that is not protected. This difference, however, will not be reflected in the condition ratings of the two specimens, unless it is manifested in their respective distress indicators.

Each distress indicator provides partial evidence (hint or contribution) for the condition of the specific pipe component. In turn, each category provides partial evidence to support the expected condition rating of the asset. The contribution of each distress indicator towards a specific category, as well as the contribution of each category towards the final condition rating, is assessed from well-documented case histories as well as from known behaviour and performance of buried pipes, engineering judgement and expert knowledge. Categories specific to PCCP and cast/ductile iron pipes that are used to assess condition ratings are shown in Table 1 and Table 2, respectively. The contribution of each distress indicator towards its respective category can be expressed linguistically or numerically, depending on its nature and available data.

For a hierarchical structure of M categories, H_j denotes a category ($j = 1, \ldots, M$), and $H_{i,j}$ denotes a distress indicator i ($i = 1, \ldots, N_j$), where N_j denotes the number of distress indicators that are included in category H_j. For example, $H_{3,4}$ represents distress indicator 3 in category 4 of the condition assessment process, while H_2 represents category 2 in the same process. Each distress indicator i is defined over its respective universe of discourse (universal scale) (Table 3 and Table 4). For example, the universe of discourse for pit depth $H_{1,2}$ (expressed as % of pipe wall thickness in Table 4) includes *no information*; $p < 10\%$; $10\% < p \leq 40\%$; $40\% < p \leq 60\%$; $60\% < p \leq 80\%$; and $p > 80\%$. The '*no information*' case, i.e., no data are available for this distress indicator, refers to ignorance (i.e.

Table 1 | Descriptions of distress indicators that influence the pipe condition for PCCP water mains

Category (Level 1)	(*j*)	Distress indicator (Level 2)	(*i,j*)	Comment
Mortar coating	1	Spalling	1,1	Spalling is often a first indicator of corrosion. Large area may indicate that corrosion is taking place over a significant surface area of pipe exterior.
		Crack type	2,1	Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur due to low hoop resistance (wire breaks?).
		Crack width	3,1	Crack width is another indicator of severity of spalling. Large widths mean that spalling is imminent.
		Crack density (frequency)	4,1	Closer crack spacing usually means the pipe is under higher stress.
		Coloration	5,1	Signs of colour/stains on concrete exterior indicate that corrosion is taking place. Often stains are precursors to spalling, i.e. corrosion products have built up.
Prestressed wire	2	Wire breaks	1,2	As the number of wire breaks increases, the factor of safety decreases and eventually leads to pipe failure.
Concrete core	3	Delamination	1,3	Delamination occurs when there is poor bonding between concrete/wire or steel/steel cylinder. This can also occur when prestressing is lost due to wire breaks.
		Crack type	2,3	Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur due to low hoop resistance (wire breaks?).
		Crack width	3,3	Crack width is another indicator of severity of spalling. Large widths mean that spalling is imminent.
		Crack density (frequency)	4,3	Closer crack spacing usually means the pipe is under higher stress.
		Hammer tapping sounding	5,3	Hammer tapping sounds can indicate delamination. It can be as simple as tapping a hammer or using the 'pulse echo' method.
		Hollow area	6,3	Aerial extent of hollow sound heard can give an idea of the seriousness of the lamination (compared with pipe surface area).
Pipe geometry	4	Out of roundness	1,4	Out-of-roundness is another indicator of wire loss that may not be evident from concrete spalling or presence of corrosion products, etc.
Joint	5	Change in alignment	1,5	Changes in joint alignment indicate pipe susceptible to ground movement. Eventually it can lead to weld failures and hence joint failure.
		Joint (internal) displacement	2,5	Joints can displace without undergoing joint misalignment and hence also an indicator of other forces at play.
		Joint diaper crack size	3,5	Crack of external diaper can give an idea of joint quality.

Journal of Water Supply: Research and Technology—AQUA | 55.1 | 2006

Table 2 | Descriptions of distress indicators that influence pipe condition for cast and ductile iron pipes

Category (Level 1)	(*j*)	Distress indicator (Level 2)	(*i,j*)	Comment
External coating (poly warp/tar/zinc)	1	Crack/tear/holiday	1,1	State of external coating will dictate how external corrosion is likely to encourage damage to the pipe.
External pipe barrel/bell	2	Remaining wall thickness	1,2	Remaining pipe wall thickness is usually obtained from NDT tests or from spot exhumations and sand blasting samples.
		Graphitization (pit) aerial extent	2,2	Aerial extent as percentage of pipe diameter x unit length indicates the size of affected area. Severe graphitization may not always mean the pipe should have failed. In practice, graphitized area can still provide some resistance – it acts as a form of sticking-plaster!
		Crack (pit) type	3,2	Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur due to low hoop resistance.
		Crack (pit) width	4,2	Crack width is another indicator of corrosion. Wide crack together with a deep pit will be more detrimental to the pipe than a narrow but shallow crack.
Inner lining/surface	3	Cement lining (epoxy) spalling (blistering)	1,3	Inner lining deterioration is often due to incompatible water chemistry or abrasion due to the presence of high water velocities and sediments.
		Remaining wall thickness	2,3	Occasionally CCTV scans can give estimates of internal corrosion pits when NDT tests are not done to get an overall picture of the pipe wall status.
		Tuberculation	3,3	Heavy tuberculation (blockage) can significantly reduce water delivery and produce red water condition.
Joint	4	Change in alignment	1,4	Changes in joint alignment indicate pipe susceptible to ground movement. Large changes can lead to leakage and eventually joint failure.
		Joint displacement	2,4	Joints can displace without undergoing joint misalignment and hence is also an indicator of other forces at play.

ambiguity), but for the sake of simplicity, it is taken as a *nil* value; i.e. weights for distress indicators that have available information are readjusted (by normalizing in that category) in the *aggregation* procedure.

Data on distress indicators can be expressed in crisp values, fuzzy values (linguistic constants), or a selection from a list (universe of discourse) of broad intervals (ranges), depending on the type of data and available knowledge for the specific distress indicator. This flexibility recognizes the fact that available data are often scarce, imprecise, vague (especially in the initial stages of applying the method) and that the physics or mechanics of the deteriorating pipe are often understood intuitively rather than rigorously. It is believed that specifying the data in this way avoids many false precisions and increases the comfort level and confidence in the proposed approach to translate distress indicators to condition ratings. Two examples to illustrate the lack of adequate knowledge are:

(1) What number of wire breaks in a PCCP pipe and its variation with time constitutes its transition from *good*

Table 3 | Universe of discourse for distress indicators of PCCP pipes

Category (Level 1)	Distress indicator (Level 2)	Universe of discourse
Mortar coating	Spalling	(no, yes)
	Crack type	(no cracks, circumferential, longitudinal – crown/invert, mixed (long. + circum.), longitudinal – spring line)
	Crack width	(no cracks, hairline, 'dime' thick, ≥ 'finger' thick)
	Crack density (spacing)	(no cracks, crack spacing ≤ 50 mm, 50 mm < crack spacing ≤ 100 mm, crack spacing > 100 mm)
	Coloration	(no stains, slight rust stains, moderate rust stains, obvious rust stains)
Prestressed wire	Wire breaks	48″ diameter: (no breaks, <5 breaks, 6 ≤ breaks < 20, 21 ≤ breaks < 40, breaks ≥ 41) 96″ diameter: (no breaks, <10 breaks, 11 ≤ breaks < 40, 41 ≤ breaks < 80, breaks ≥ 81)
Concrete core	Delamination	(no, may be, yes)
	Crack type	(no cracks, circumferential, longitudinal - crown/invert, mixed (long. + circum.), longitudinal – spring line)
	Crack width	(no cracks, hairline, 'dime' thick, ≥'finger' thick)
	Crack density (spacing)	(no cracks, crack spacing ≤ 50 mm, 50 mm < crack spacing ≤ 100 mm, crack spacing > 100 mm)
	Hammer tapping sounding	(very firm, firm, slightly hollow, moderately hollow, very hollow)
	Hollow area	(no hollow area, hollow area < 2%, 2% ≤ hollow area < 4%, 4% ≤ hollow area < 6%, hollow area ≥ 6%)
Pipe geometry	Out of roundness	(round – no obvious bulge, bulge < 1% of diameter, bulge between 2 and 3% of diameter, bulge > 3% of diameter)
Joint	Change in alignment	(no change, angle < 22.5° or Δ alignment < 5%, 6% < Δ alignment < 10%, angle > 22.5° or Δ alignment > 11%)
	Joint (internal) displacement	(no displacement, displacement < 5 mm, 5 mm < displacement < 10 mm, displacement > 10 mm)
	Joint diaper crack size	(no cracks, hairline, 'dime' thick, ≥'finger' thick)

to *poor* conditions? The same number of wire breaks in low and high pressure rated mains or in small- and large-diameter mains would not have the same consequences if all other parameters remain the same. Engineering judgement would indicate that a specific number of wire breaks has less effect on large-diameter mains than on small-diameter mains. The relationships between the loss of structural capacity and the number of wire breaks and their spatial sparsity for PCCP pipes are not yet available.

(2) A cast iron pipe segment with a single corrosion pit depth of 30% of wall thickness would qualify a pipe as

Table 4 | Universe of discourse for distress indicators of cast and ductile iron pipes

Category (Level 1)	Distress indicator (Level 2)	Universe of discourse
External coating (poly warp/tar/zinc)	Crack/tear/holiday	(no damage, slightly damaged, moderately damaged, highly damaged)
External pipe barrel/bell	Pit depth	(pit depth < 10%, 10% < pit depth < 40%, 40% < pit depth < 60%, 60% < pit depth < 80%, pit depth > 80%)
	Graphitization (pit) aerial extent	(affected area < 20%, 20% < affected area < 40%, 40% < affected area < 60%, 60% < affected area < 80%, affected area > 80%)
	Crack (pit) type	(no cracks, circumferential, longitudinal - crown/invert, mixed (long. + circum.), longitudinal – spring line)
	Crack (pit) width	(no cracks, hairline, 'dime' thick, ≥ 'finger' thick)
Inner lining/surface	Cement lining (epoxy) spalling (blistering)	(no, yes)
	Remaining wall thickness	(pit depth < 10%, 10% < pit depth < 40%, 40% < pit depth < 60%, 60% < pit depth < 80%, pit depth > 80%)
	Tuberculation	(diameter reduced by < 20%, 20% < reduced diameter < 40%, 40% < reduced diameter < 60%, 60% < reduced diameter < 80%) diameter reduced by > 80%
Joint	Change in alignment	(no change, angle < 22.5° or Δ alignment < 5%, 6% < Δ alignment < 10%, angle > 22.5° or Δ alignment > 11%)
	Joint displacement	(no displacement, displacement < 5 mm, 5 mm < displacement < 10 mm, displacement > 10 mm)

in *good* condition but it is not clear how the pipe condition rating would differ if it had many sparsely spaced pits with depths that exceed 20% of wall thickness compared with a pipe that had a few closely spaced pits with depths that exceed 30% of wall thickness. The issue of how the condition rating changes with the sparsity of corrosion pits and their depths in cast and ductile iron pipe segments needs to be explored further.

The FSE process described here involves three steps, (1) *fuzzification* of raw data (measurements of the distress indicators); (2a) *aggregation* of distress indicators towards their respective categories; (2b) *aggregation* of categories towards the condition rating; and (3) *defuzzification* that adjusts the condition rating to a practical crisp format. These four steps are described below.

Fuzzification of raw data

It is assumed that each and every distress indicator $H_{i,j}$ is associated with an underlying fuzzy set $C_{i,j}$, which is defined by n linguistic constants and a specific universe of discourse. In this paper, $n = 7$, which corresponds to condition states *excellent*, *good*, *adequate*, *fair*, *poor*, *bad* and *failed*. Raw data for a given distress indicator $H_{i,j}$, whether crisp, fuzzy or predefined interval-valued, are mapped (or fuzzified) onto $C_{i,j}$. For example, in the case of the distress indicator 'pit depth' in category 2 for CI mains (Table 4), the universe of discourse represents depths of pits that range from 0% to >80% of the pipe wall thickness. In another example of distress indicator, 'spalling', the universe of discourse comprises just two logical variables *yes* and *no*. In both examples the user-selected raw data are mapped onto the corresponding 7-tuple fuzzy sets

$C_{i,j}$. It should be noted that for all distress indicators, the universes of discourse have to be unidirectional: i.e. arranged so that contribution towards $C_{i,j}$ are in monotonically increasing order. This unidirectional order for the universe of discourse that correspond to each category of distress indicators is essential to ensure that the final aggregative effect for all categories is a convex fuzzy set. After fuzzification, each distress indicator is represented by its corresponding 7-tuple fuzzy set $C_{i,j.}$ For example, the fuzzy set that represents the distress of 15 wire breaks observed in a PCCP pipe is (0, 0, 0.3, 0.7, 0, 0, 0), which can be interpreted as

$$\left(\frac{0}{excellent}, \frac{0}{good}, \frac{0.3}{adequate}, \frac{0.7}{fair}, \frac{0}{poor}, \frac{0}{bad}, \frac{0}{failed}\right).$$

Rather than treating a distress indicator with '*no information*' as a case that the distress indicator is unimportant and assign a *nil* value, as previously discussed, a possible additional alternative is to assign it memberships that correspond to *excellent* (optimistic) and *failed* (pessimistic) condition states: i.e. (1, 0, 0, 0, 0, 0, 0) and (0, 0, 0, 0, 0, 0, 1), respectively. In practice, the FSE would be conducted for both of these scenarios to gauge the level of ignorance.

Aggregation of distress indicators

Relative degrees of influence (importance or evidential credibility) have to be assigned in order to aggregate distress indicators towards their respective categories (level 2). Let $W_{i,j}$ denote the relative weight of distress indicator i towards category j. Weight values are established through expert opinion or Delphi method-based surveys (Lee and Kim 2001). The Delphi method comprises a series of questionnaires designed to elicit and develop individual responses to the problems posed to a pre-selected group of experts. It allows for anonymity, controlled feedback, and statistical analysis of responses (Fowles 1978). Thus, expert opinion could be expressed using the linguistic terms *extremely important*, *very important*, *important*, *moderately important*, and *unimportant*. The weights of all distress indicators within a category are normalized to a sum of 1 prior to the application of the aggregation steps. The aggregation process of distress indicators towards their respective categories (level 2) is given by:

$$H_j = [W_{1,j} \; \ldots \; W_{i,j} \; \ldots \; W_{N_j,j}] \bullet [C_{1,j} \; \ldots \; C_{i,j} \; \ldots \; C_{N_j,j}]^T \quad (1)$$

where '•' represents matrix multiplication. Since $C_{i,j}$ are 7-tuple fuzzy sets and $W_{i,j}$ are scalars, H_j is in fact a 7-tuple fuzzy set that represents the aggregated contribution of category j towards the final outcome: i.e. condition rating.

Aggregation of categories

Relative degrees of influence (importance or evidential credibility) have to be assigned, in much the same way as in level 2 aggregation described above, in order to aggregate categories towards the condition rating (level 1). W_j denotes the relative weight of category j towards the condition rating. The aggregation process is given by,

$$C = [W_1 \; \ldots \; W_j \; \ldots \; W_M] \bullet [H_1 \; \ldots \; H_j \; \ldots \; H_M]^T \quad (2)$$

where C is a 7-tuple fuzzy set representing the condition rating of the asset. As at level 1, weight values are established through expert opinion.

Adjustment of the condition rating to a practical format using defuzzification

Kleiner *et al.* (2006) discussed the fact that a fuzzy pipe condition with support for more than three contiguous tuples would be contrary to intuitive expert opinion; e.g. an expert would never assign a condition rating to an asset, in which there are positive membership values to, say, *excellent* and *poor* condition states simultaneously. In this final step in the FSE process, adjustment is made to fuzzy set C so that it has a maximum of three contiguous tuples' support (non-zero membership values to a maximum of three subsets).

If fuzzy set C obtained from Equation 2 has support to no more than three contiguous condition states it is considered the 'true' condition rating of the asset. Otherwise an adjustment is carried out in the following manner. First, C is defuzzified using the centroidal method proposed by Yager (1980). Second, the crisp value is re-mapped on the universe of discourse of fuzzy set C. Third, if there is membership value that is greater than a pre-set threshold, the excess is equally divided to the adjacent condition states (using the principle of insufficient reason). For example, if re-mapping the defuzzified value of *C* yields a fuzzy set (0, 0.1, 0.9, 0, 0, 0, 0), and the threshold is selected to be, say, 0.7, then the adjusted *C* becomes (0, 0.2, 0.7, 0.1, 0, 0, 0). It should be noted that this scheme is just one of several possible adjustment schemes.

The complete three-step FSE procedure is shown schematically in Figure 1 with an example of a 5-tuple fuzzy set for brevity and simplicity. The left half of Figure 1 represents the first step (1) of *fuzzification* of raw data, within the FSE process. Each distress indicator within a category *j* is represented by triangular fuzzy numbers (TFNs); e.g. universe of discourse of wire breaks (0, 20, 40, 60, >100) in a PCCP pipe corresponds to condition states (*good*, *adequate*, *fair*, *poor*, *bad*). Thus the membership to these conditions for, say, 40 breaks, would be given by (0, 0, 1, 0, 0). As discussed earlier, the weight for each distress indicator $W_{i,j}$ would be established through expert opinion. The first part of the second step (2a) of *aggregation* of distress indicators for category 1 is represented in the top right-hand box of Figure 1. The *aggregation* of all categories, *M*, which is the second of the second step (2b), leads to the bottom right-hand box in Figure 1. The last step (3) is the *defuzzification* of condition rating that leads to two contiguous states as discussed above.

COMBINING NON-COMMENSURATE DISTRESS INDICATORS

As discussed earlier, each distress indicator is expressed as a fuzzy/interval-valued/crisp variable, defined over its respective universe of discourse (Table 3 and Table 4). One or more distress indicators will be typically detected by a specific inspection method. Most categories (level 1) and distress indicators (level 2) are non-commensurate; i.e. a significant hollow sound over *x*% of a PCCP pipe is distinct

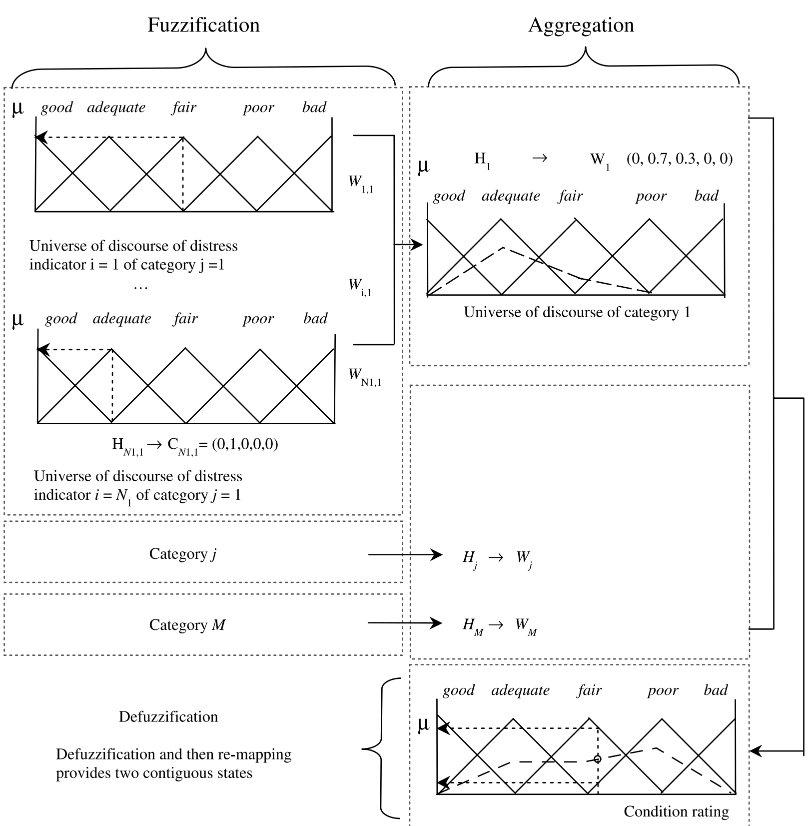

Figure 1 | Schematic of the fuzzy synthetic evaluation (FSE) process.

from Y consecutive wire breaks. The mapping (fuzzification) of each distress indicator should be pursued in manner to ensure equivalency; i.e. be on equal footing, between any two measures (attributes) of distress that reflect the same condition state. Current state of knowledge does not help to establish what are x and Y. Thus, the mapping of each distress indicator can only be established through improved understanding of the physiochemical processes of pipe deterioration and the ability to realistically define the universe of discourse for each distress indicator. In this paper, the mapping of distress indicators was largely based on known behaviour and performance of buried pipes, engineering judgement and information derived from numerous published case histories. Gross discrepancies in condition ratings can arise if the equivalency between any two measures of distress that reflect the same condition state is inappropriately mapped.

The weights at level 1 (Equation 2) reflect the relative importance of the categories for a specific pipe type while the relative importance between distress indicators within a specific category is specified by weights at level 2 (Equation 1). These aforementioned weights at level 2, besides 'importance', would also include the confidence in the accuracy and reliability of the inspection methods to detect and quantify the level of distress if no additional weights were introduced. In the proposed framework, relative confidence in the inspection methods is expressed through the introduction of weights (credibility factors) to the condition ratings as discussed by Kleiner *et al.* (2006). Of course, imprecision of measurements and the relative reliability of different inspection methods and operators introduces additional difficulties in establishing weights discussed above.

FUZZY CONDITION RATING FOR VARIOUS PIPE TYPES

Figure 2 schematically shows how the condition of PCCP, cast and ductile iron pipes is affected by changes in distress indicators. PCCP, cast and ductile iron pipes undergo ageing as they are subjected to changing external and internal environments. The deterioration process is continuous and its physical manifestations are often discernable in distinct stages: corrosion pits, wire breaks, spalling, etc., as indicated in Figure 2.

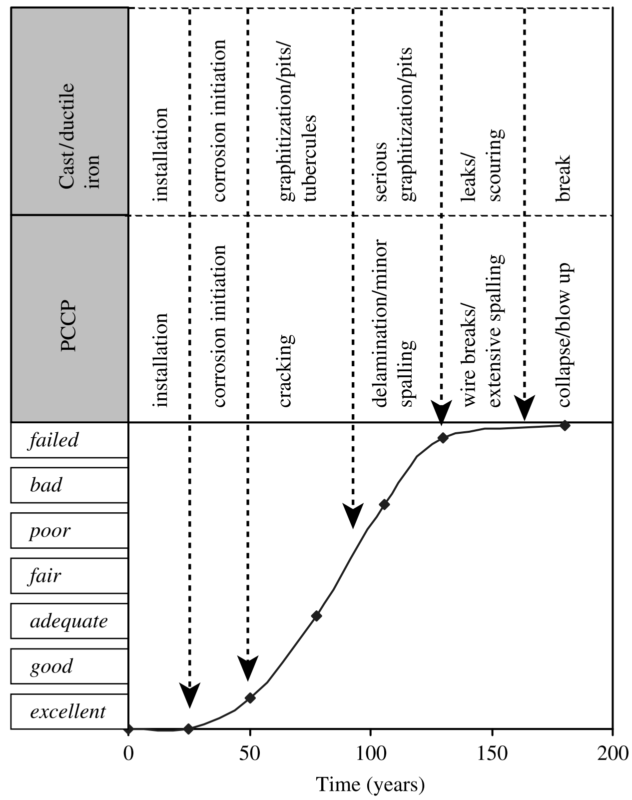

Figure 2 | Schematics of changing pipe conditions as the pipe deteriorates (time scale can vary).

Table 1 provides a brief description on how each distress indicator is likely to influence the condition rating of PCCP pipe. The information was gathered from the literature (publications, manuals, etc.) that is available on the behaviour and performance of buried pipes. The role of most distress indicators for PCCP pipes was confirmed in consultation with J. Galleher (personal communication, 2003), an expert in the management of PCCP pipes in San Diego County Water Authority, California.

Table 2 gives a brief description of how each distress indicator is likely to influence the condition rating of cast/ ductile iron mains. Several studies (De Rosa and Parkinson 1985; Bonds *et al.* 2005) indicate that corrosion rates for both cast and ductile iron pipes are similar for all practical purposes. Here, too, information was gathered from available literature (publications, manuals, etc.). Much more information, including case histories of failures and investigations of failure mechanisms, is available on cast and ductile iron pipes compared with PCCP pipes.

The lists in Tables 1 and 2 include most of the important categories and distress indicators within each category. However, as new knowledge becomes available and as new NDE technologies are developed, these lists could be updated and/or expanded along with the associated weights.

EXAMPLES

Two examples, one for PCCP and the other for a cast iron main, are presented to illustrate how the FSE process described above can be used to translate distress indicators to condition ratings. Data obtained from a US public utility for one segment of a 2,400 mm (96″) diameter PCCP pipe are shown in Table 5. The pipes were installed in 1978 and the particular pipe segment discussed here has been inspected three times since installation. The pipe was inspected visually (walk through) and using pulse echo (hammer tapping) in 1997 to detect concrete core conditions. As the RFEC/TC inspection technology for PCCP pipes became commercially available in 1999, the pipe was inspected, using this technology, in 1999 and 2002 to detect the number of wire breaks.

For both examples, expert opinion was expressed through the use of weights of 9, 7, 5, 3, and 1 for the linguistic terms, *extremely important*, *very important*, *important*, *moderately important*, and *unimportant*, respectively. As explained earlier, these weights are normalized prior to the application of the aggregation steps. The threshold value used for adjustment of the condition rating was set to 0.85 for both examples.

Since there was no information on the condition rating of the pipe just after installation, it was assumed to be primarily in *excellent* condition, represented by the fuzzy set (0.9, 0.1, 0, 0, 0, 0, 0). The visual inspection in 1997 indicated that the pipe segment had no spalling and no cracks on the inner side of the concrete core. The lack of colouration or stains also confirms this observation. The pulse echo test response of 'very firm' on the same pipe segment at the time of the visual inspection confirmed that the concrete core was intact. The condition rating of the pipe segment was obtained as (0.09, 0.85, 0.06, 0, 0, 0, 0) after the application of Equations 1 and 2 and after adjustment using the cited threshold value; i.e. pipe segment is primarily in the *good* condition state with a membership value of 0.85. It must be noted the membership of 0.85 is not a coincidence but rather a result of the threshold membership value set to 0.85.

Two subsequent inspections of the same pipe segment in 1999 and 2002 using the RFEC/TC method resulted in the detection of 5 and 15 wire breaks, respectively, in the PCCP pipe segment. The corresponding condition state of the pipe segment inspected in 1999 was predominantly *good* while condition state for the inspection done in 2002 was *fair* with a strong leaning towards *adequate*. The pipe segment condition rating has changed from predominantly *good* to *fair-adequate* during a period of 3 years, which can be judged to be a fairly rapid deterioration rate, assuming the numbers of wire breaks detected were accurate.

Table 5 | Distress indicators for 2,400 mm (96″) diameter PCCP installed in 1978. APS: inspection history (membership to states) for pipe ID 4078

							Condition rating						
Year	Method	# Wire breaks	Spalling	Cracks	Coloration	Pulse-echo sound	E	G	A	F	P	B	X
1978							0.9	0.1	0	0	0	0	0
1997	Visual	–	None	No cracks	No stains	Very firm	0.09	0.85	0.06	0	0	0	0
1999	RFEC/TC	5	–	–	–	–	0.06	0.85	0.09	0	0	0	0
2002	RFEC/TC	15	–	–	–	–	0	0	0.47	0.53	0	0	0

E = excellent, G = good, A = adequate, F = fair, P = poor, B = bad, X = failed

Table 6 | Distress indicators for 915 mm (36″) diameter cast iron mains installed in 1917 in Gloucester Street, Ottawa

					Condition rating						
Year	**Method**	**Remaining wall thickness (%)**	**Tuberculation**	**Change in joint alignment**	**E**	**G**	**A**	**F**	**P**	**B**	**X**
1917					0.9	0.1	0	0	0	0	0
1986?	CCTV	>90	Moderate	–	0.1	0.85	0.05	0	0	0	0
2002	CCTV/coupon	10–40	Moderate	<5%	0	0	0.81	0.19	0	0	0

E = excellent, G = good, A = adequate, F = fair, P = poor, B = bad, X = failed

The inspection data for the cast iron mains shown in Table 6 is illustrative and not based on any real data obtained from inspections. The principal characteristics of the unlined cast iron mains are similar to a 915 mm (36″) diameter pipe installed in 1917 in downtown Ottawa, Ontario. The undated (assumed to have taken place in 1986) CCTV (closed circuit television) inspection found that the internal pipe surface had tuberculation with an estimated thickness of 10 to 12 mm, estimated to reduce internal pipe diameter by less than 20%. It was further assumed that a subsequent inspection in 2002 found that a specific cast iron mains segment had several areas of graphitization (aerial extent estimated to be less than 20% of pipe surface area) with a remaining wall thickness of between 10 and 40% and estimated change (from CCTV footage) in joint alignment of less than 5%. It was also assumed that degree of tuberculation had remained unchanged since the last inspection in 1986 and that the condition rating immediately post-installation was *excellent*; i.e. $C = (0.9, 0.1, 0, 0, 0, 0, 0)$.

The resulting condition ratings obtained for the years 1986 and 2002 were (0.1, 0.85, 0.05, 0, 0, 0, 0) and (0, 0, 0.81, 0.19, 0, 0, 0), respectively. The condition of the pipe deteriorated in 16 years from predominantly *good* to predominantly *adequate* with a strong leaning towards *fair*.

DISCUSSION

The condition rating of a specific pipe segment largely depends on the accuracy of observed distress indicators, which in turn depend on the reliability of the inspection methods. One approach to reflect the reliability of the inspection methods is through the introduction of weights applicable to distress indicators at level 2 as discussed previously. However, it is difficult to distinguish how much of a weight reflects the relative importance of the distress indicators within a specific category and how much of it corresponds to the reliability of the inspection methods. A cursory way to account for this is through the introduction of weights applicable to condition ratings as suggested by Kleiner *et al.* (2006).

It is recognized that the FSE process, as described in this paper, fails to address issues that are important in the translation of distress indicators to condition ratings: e.g. establishment of equivalency in the combination of non-commensurate distress indicators, fusion of incomplete and/or conflicting data from different sources, which can be handled using Dempster-Shafer theory of evidence (Dempster 1967; Shafer 1976). The type of uncertainty handled through the fuzzy synthetic evaluation process relates only to vagueness (fuzziness) whereas the other component of uncertainty, ambiguity (which includes non-specificity and conflict (dissonance)), is not addressed explicitly in this study. These uncertainties need to be studied in order to provide more realistic condition ratings, and stress the importance of using hybrid soft computing methods (e.g. Fuzzy-Dempster-Shafer; Najjaran *et al.* 2005). Further research needs to be pursued to incorporate the issues highlighted into the proposed framework.

It is not unusual that data (observations or evidence) obtained through the use of inspection methods, which can incorporate one or more non-destructive or visual techniques, may reinforce (confirm) or refute (contradict) previously collected data. Therefore the condition rating for a specific pipe segment needs to be continually updated as additional evidence becomes available. Possible uncertainty-based approaches for data fusion include the Dempster-Shafer theory of evidence (Dempster 1967; Shafer 1976), Bayesian analysis and theory of hints (Kohlas & Monney 1995). Nonetheless, it must be emphasized that a deep understanding of the physicochemical processes would still be required to quantify the 'strength' of the evidence or a hint. The proposed FSE process provides a platform to incorporate evidential reasoning to update condition ratings as additional data on distress indicators become available from different sources.

SUMMARY

The condition rating of large-diameter transmission mains reflects an aggregate (overall) state of its health. Distress indicators are physical manifestations of the ageing process. The type (or form) and location of observed distress indicators in large-diameter mains are dependent on the pipe material, its surrounding environment and the cumulative effects of stresses to which it was subjected. The physicochemical processes that promote ageing are not yet well understood. Fuzzy techniques can incorporate engineering judgement and experience to translate distress indicators (observed through visual inspection or NDE techniques) to condition ratings. The use of the fuzzy synthetic evaluation process is proposed since the encoding of distress indicators into the condition rating is inherently imprecise and involves subjective judgement.

ACKNOWLEDGEMENT

This paper is based on a research project, which was co-sponsored by the American Water Works Association Research Foundation (AwwaRF), the National Research Council of Canada (NRC) and water utilities from the United States, Canada and Australia.

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First received 23 August 2005; accepted in revised form 3 November 2005