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Non-destructive Inspection Techniques to Determine Structural Distress Indicators in Water Mains

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Abstract

The need to inspect ageing pipes in a deteriorating water supply system is recognized by most water utilities. The response to this need has resulted in several developments to inspect specific pipe sizes and pipe materials. Some of these developments have led to commercial products while others are still at an experimental stage.

From the pipelines owner's perspective, two immediate questions arise: (1) which pipes to inspect and when and (2) what are the appropriate techniques or technologies available for inspecting pipes? The first question is discussed in terms of *failure management* for small diameter mains and *failure prevention* for large diameter mains.

The available inspection technologies are discussed in terms of the basic principles (physics) and the advantages and limitations of each technology with respect to their application to field inspections.

INTRODUCTION

Exposure of water mains to aggressive environmental conditions and deleterious reactions can lead to significant deterioration so as to undermine their ability to deliver safe drinking water reliably. The life cycle of a typical buried pipe can be described by the so-called "bathtub" curve as shown in Fig. 1. It describes the instantaneous failure probability (hazard rate) during the pipe life and the bathtub curve often distinguishes between three phases during that life. The first phase, also known as the "burn-in" phase, describes the period early after installation, in which breaks occur mainly as a result of faulty installation or faulty manufacturing. These breaks emerge gradually and are fixed in a declining frequency. Once the pipe is purged of these "early" problems, it goes into phase two, in which the pipe operates relatively trouble free, with a low failure frequency resulting from random phenomena such as unusual heavy loads, third party interference, etc. The third phase, also called "wear-out phase," depicts a period of increasing failure frequency due to pipe deterioration and ageing. Not every pipe experiences every phase and the length of the phases may vary dramatically for various pipes and under different conditions.

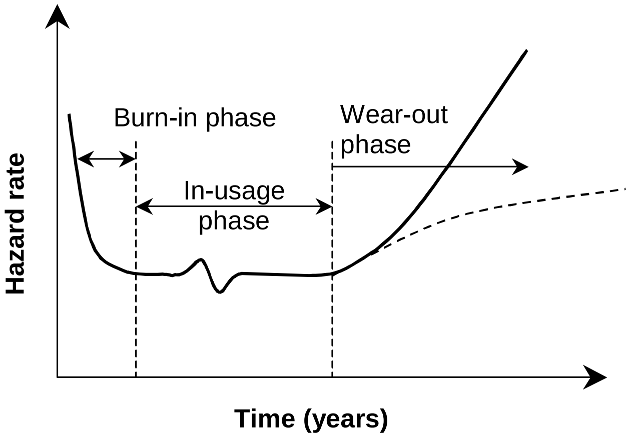

Fig. 1 The bathtub curve of the life cycle of a buried pipe.

Alternatively, the various phases in the deterioration of structural reliability (expressed here as the factor of safety) that ultimately lead to the failure of the water main are shown in Fig. 2.

Older water mains are usually made of cast iron (CI), which are pit or spun cast and asbestos cement (AC) while the newer mains are largely made of ductile iron (DI) or poly-vinyl chloride (PVC). In an aggressive environment, corrosion in CI takes the form of graphitisation (Makar and Rajani, 2000) while in DI pipes pitting is the main form. Asbestos cement and concrete pipes in contact with low pH water lead to material softening (Slaats *et al.*, 2004). PVC water mains have not been used long enough to establish a definite deterioration mechanism. Steel and prestressed concrete cylinder pipe (PCCP) are typically used for large transmission mains where pipe diameters are typically greater than 300 mm (12”). PCCP is a composite pipe made of concrete core, steel cylinder, prestressed steel wires and external mortar coating. PCCP pipe exposed to aggressive soils can lead to corrosion of the prestressed steel wires and ultimately to a catastrophic failure if a sufficient number of wires break under normal operating pressures.

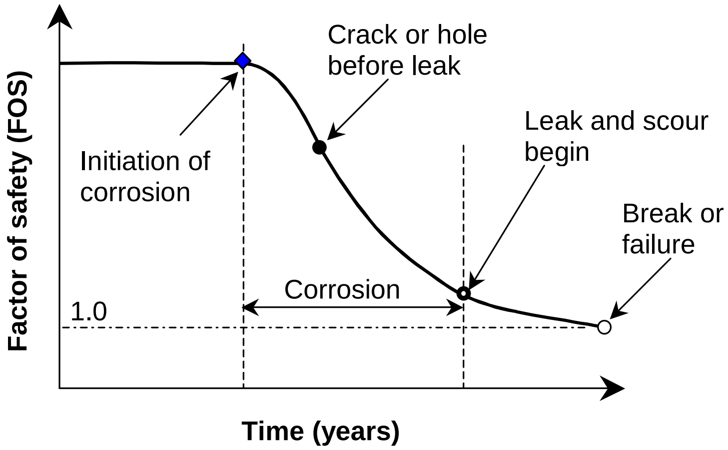

Fig. 2 Decrease in factor of safety with time.

Breakage is likely to occur when the environmental and operational stresses act upon pipes whose structural integrity has been compromised by corrosion pitting, degradation, fracture, creep, material softening, scour produced by a significant leak, inadequate installation or manufacturing defects. Pipe breakage types were classified by O'Day *et al*. (1986) into three categories: (1) circumferential breaks, caused by longitudinal stresses; (2) longitudinal breaks, caused by transverse stresses (hoop stress); and (3) split bell, caused by transverse stresses on the pipe joint. This classification may be complemented by an additional breakage type i.e., holes due to corrosion. Circumferential breaks due to longitudinal stress are typically the result of one or more of the following occurrences: (1) thermal contraction (due to low temperature of the water in the pipe and the pipe surroundings) acting on a restrained pipe, (2) bending stress (beam failure) due to soil differential movement (especially clayey soils) or large voids in the bedding near the pipe (resulting from leaks), (3) inadequate trench and bedding practices, and (4) third party interference (e.g., accidental breaks, etc.). The contribution of internal pressure in the pipe to longitudinal stress, although small, may increase the risk of circumferential breaks when it occurs simultaneously with one or more of the other sources of stress.

Longitudinal breaks due to transverse stresses are typically the result of one or more of the following factors: (1) hoop stress due to pressure in the pipe, (2) ring stress due to soil cover load, (3) ring stress due to live loads caused by traffic, and (4) increase in ring loads when penetrating frost causes the expansion of frozen moisture in the ground.

The need to inspect pipes to identify distress indicators, e.g., cracks, corrosion pits, broken prestressing wires, mortar spalling, etc., at some time in the "wear-out phase" is accepted by most water utilities. Distress indicators are forms of deterioration that have not yet led to pipe failure. Thus, the principal associated questions are: (1) which pipes to inspect and when and (2) what are the appropriate techniques or technologies available to inspect pipes? In this paper, these questions are addressed in broad terms to guide the utility engineer in taking informed decisions.

The three main drivers for pipe renewal or replacement are the contribution of the pipe to water quality degradation, pipe hydraulic capacity and its structural reliability. In this paper only structural issues and related distress indicators are discussed, however a holistic approach should be considered in practice.

WHICH PIPES TO INSPECT (TRANSMISSION OR DISTRIBUTION MAINS) AND WHEN?

Failure risk in a water distribution network

The failure of a distribution system is broadly defined as the inability (momentary or extended) to meet any of the following performance criteria:

- Provide all regular demand for water at an acceptable pressure.
- Be capable of providing emergency flows (e.g., for fire fighting) at an acceptable pressure.
- Provide safe drinking water.

- Provide water that is acceptable to the consumer in terms of aesthetics, odour and taste.
- Be economically efficient.

As pipes age they deteriorate, resulting in increased failure frequency. In the context of reliability engineering and risk management, the definition of risk depends on the type of asset or system (Henley and Kumamoto, 1981). For buried pipes one can define the risk of any type of failure as the expected magnitude of the consequences of failure(s), i.e.,

$$\text{Risk of failure} = E(\text{failure consequence}) = f(\text{probability of failure, costs of failure}) \qquad (1)$$

Probability of failure (failure frequency)

The probability of failure can be assessed in different ways, some more rigorous than others, depending on the type of failure and available data.

The probability of a water main failure due to structural deterioration can be estimated using mechanistic models that compare stresses acting on a pipe to its residual strength. The main problem with these models (assuming they are robust and comprehensive) is that they require a lot of data that are either unavailable or very costly to obtain, for even a modest portion of a distribution network, because of spatial variability. Repeated condition assessments, using non-destructive evaluations (NDE) techniques, can assist in the calibration of some of the parameters of these models, and improve their accuracy. Alternatively, a more manageable approach is to develop empirical relationships between the pipe, its exposure to the external and operational environments and its observed failure frequency. These empirical models typically over-simplify a complex reality in order to achieve “80% of the answer with 20% of the effort”. This goal of 80-20 is not always achieved because of the very nature of the over simplification or because of insufficient historical failure data.

It should be noted that some water main failures such as those caused by accidental or malicious third party interference cannot be assessed with either of these approaches. These may require qualitative-quantitative approaches such as fault trees, or actuarial type calculations.

Consequence (Cost) of failure

The costs of a water main failure event may be classified into three categories: (a) direct, (b) indirect, and (c) social costs. While direct costs are relatively easy to quantify in monetary terms, indirect costs may require much more effort, and social costs are often the most difficult to describe and assess (Rajani and Kleiner, 2002).

Strictly speaking the magnitude of failure consequence is a random value because no two failures have the same consequences. The failures of small distribution mains are usually repaired with little effort and typically collateral damage is relatively small. The failures of large transmission mains are relatively rare, and because only a few water utilities attempt to assess total failure damage, there are currently insufficient data to assign probability distributions to failure costs. More research is required to gain a better understanding of the true magnitude of indirect and social consequences of all failure types.

Risk of Failure

Risk mitigation can be achieved by reducing failure probability and/or its cost, as risk depends both on the probability and the cost of failure (equation (1)). As the distribution system ages, its components deteriorate and the probability of failure increases. This is true for structural failure as well as for hydraulic failure and many types of water quality failures. In some cases, it can be argued that the cost of failure is also likely to increase over time, e.g., when a pipe is located in a rapidly developing area, but generally it is assumed that failure cost is not time-dependent.

Measures to mitigate risk from the cost side are possible but rather limited in scope. Examples include: (i) Timely response by a well-trained pipe repair crew will reduce the cost of repair as well as water loss and collateral damage resulting from a main break. (ii) A good monitoring program will initiate fast action to communicate to the public any water safety failure, thus minimising the level of exposure to the low quality or unsafe drinking water. (iii) An adequately sized storage tank will reduce the vulnerability of a hospital to a hydraulic failure.

It appears that mitigating risk on the failure frequency side has a greater potential because theoretically, one can reduce failure frequency to nearly zero (thus reducing risk to nearly zero) albeit at a very high cost. It follows that a rigorous decision process should find a balance between the risk of failure and the cost to mitigate it. Fig. 3 illustrates how this balance varies over time. As long as the pipe continues to age and deteriorate without renewal, its probability of failure (or failure frequency) increases and the risk increases as well (note that here the risk is expressed in discounted expected cost). At the same time, the discounted (or the present value of) cost declines as pipe renewal is delayed.

The total expected life-cycle cost is the sum of the total expected cost of failure and the cost of pipe renewal. The total expected life-cycle cost curve typically forms a convex shape, whose minimum point depicts the optimal time of renewal (t^*). This point also depicts the time at which the marginal decrease in the discounted cost of renewal equals the marginal increase in the discounted expected risk – this is the balance mentioned above between the risk of failure and the cost to mitigate it. The same type of analysis can be done to include risk mitigation on the failure consequence side. A similar balance should be sought between the investment required to reduce failure consequence (e.g., build a storage tank in a hospital, or an advanced monitoring system) and the reduction in risk it might achieve.

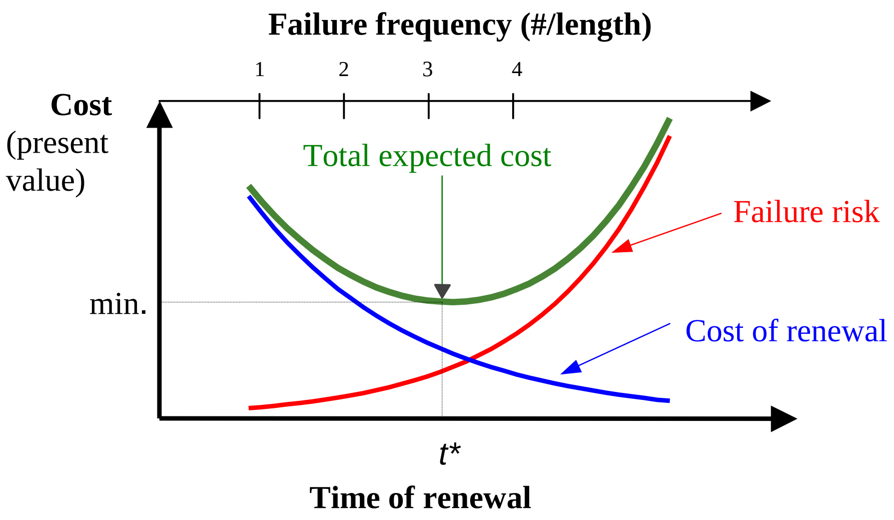

Fig. 3 Deciding when to renew a water main with a low cost of failure.

The top horizontal axis of the graph in Fig. 3 indicates that the optimal renewal time is obtained at a failure frequency of about 3 events per unit length. This represents a typical case of structural failure in small diameter distribution mains, where a given threshold of breakage frequency can be tolerated because the cost of failure is relatively low. This means that the preferable strategy in this case is to pursue *failure management* (frequency of occurrence) rather than attempt to prevent failure altogether.

In Fig. 3 the curve depicting total cost looks deeply convex with a clear minimum point at *t**. This is a rather idealized case, which may change in some cases. When ageing rate (i.e., the rate at which failure frequency increases) is similar in magnitude to the discounting factor, the convexity of this curve can become quite flat, and the point of minimum cost becomes less crisp. When the cost of failure is relatively low compared to the cost of renewal and the discounting factor relatively high, the curve can take the shape of the “hammock-chair” as described by Herz (1999), with no definite minimum, indicating that renewal should theoretically be postponed indefinitely.

Two points should be highlighted with respect to the convexity of the total cost curve. First, taking into consideration the entire cost of failure, including direct, indirect and social costs, will reduce the ratio between the cost of failure and the cost of renewal, which will push the point of minimum towards earlier renewal and increase the convexity of the total cost curve. Second, the discounting factor (or rate) should be a social discounting factor, which is invariably lower than a financial one. The social discounting factor can be perceived as a means to distribute available resources over time, or in other words “...discounting acts to distribute benefits today, paid for tomorrow” (Swartzman, 1982). Consequently, the selection of the discount rate reflects the political and ethical attitudes of the decision-maker. The deeper the discounting the more we would tend to reap benefits today and let future generations pay. Selecting a relatively low discount rate will push the point of minimum towards earlier renewal and increase the convexity of the total cost curve.

Fig. 4 shows the case of large transmission mains where the ratio between the cost of failure and the cost of renewal is significantly smaller. The optimal renewal timing is at a very low failure frequency. This means that it might be economical to take extra measures (and incur extra expense) to try and anticipate imminent failures, i.e., *failure prevention*, rather than *failure management*.

With regard to structural failures, when the cost of failure is relatively low and failure frequency can be tolerated, it is often (but not always) sufficient to rely on empirical models using historical breakage patterns to predict future failure rates. However, high failure costs may justify the use of extra measures to anticipate failures and prevent them in a proactive approach. These measures could include inspection and condition assessment using NDE techniques in conjunction with physical/mechanical models. Non-destructive evaluations techniques can be used at two levels: first, as a snapshot of the pipe condition at a given time in order to determine if immediate intervention is required, and second, using subsequent inspections to determine the rate of deterioration. It is inevitable that the costs of applying NDE techniques will decrease as they become widely available and easier to use. Consequently, their use will become economically viable for larger portions of the distribution system, until eventually all water mains will be periodically inspected using NDE techniques.

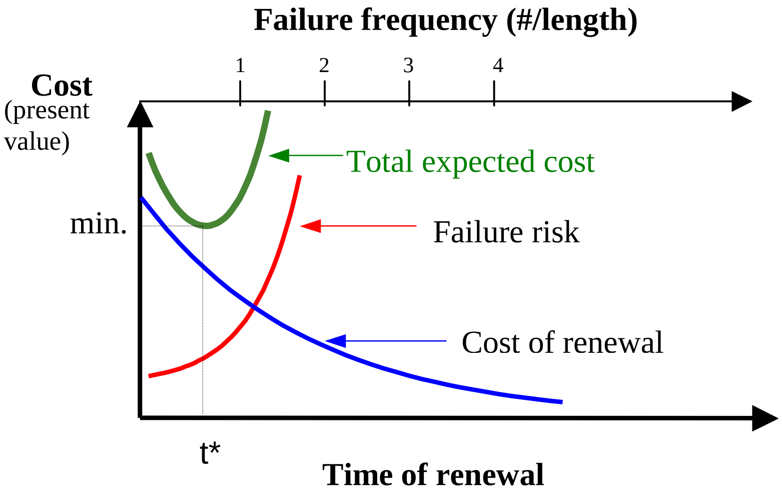

Fig. 4 Deciding when to renew a water main with a high cost of failure.

It should be emphasized that the life-cycle cost curves depicted in Fig. 3 and Fig. 4 are qualitative and idealized. True costs are often hard to come by and are subject to large variations, as are true deterioration rates. Consequently, determination of the optimal time for renewal (*t**) requires many simplifying assumptions.

INSPECTION TECHNOLOGIES

It is important to understand the properties of pipe materials and buried pipe behaviour and associated deterioration mechanisms prior to discussion of inspection technologies.

These discussions are succinct since more information is available elsewhere and appropriate references are provided as required.

Pipe Materials

The types of pipe material vary from country to country or even from city to city. Fig. 5 shows the distribution of pipe materials within existing (1990) water supply networks (data do not distinguish between pipe sizes but probably a large proportion of these pipes are within diameter range of 100 mm (4”) to 250 mm (10”)) in European countries. Spain and the Netherlands have the largest proportion of asbestos cement pipes while United Kingdom and Switzerland have the largest proportion of cast iron mains. Over 70% of pipes in Finland’s water supply systems are plastic.

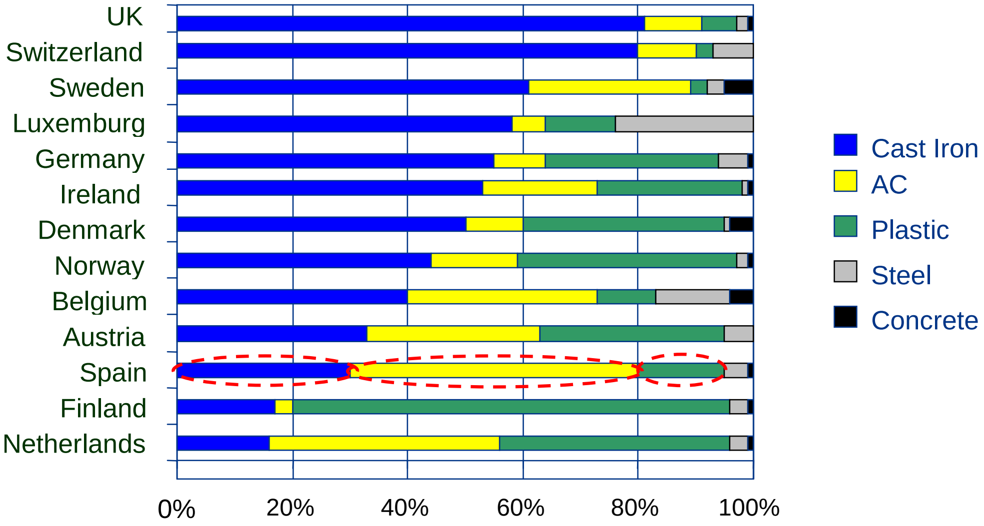

Fig. 5 Pipe materials (Bueken, 2004) in Europe.

The mechanical and thermal properties of the pipe materials are shown in Table 1. The strains to failure of cast iron and asbestos cement are significantly less than those of ductile iron and plastic pipes. It is also worth noting that thermal expansion coefficient of plastic pipes (PVC and PE) is 7 to 20 times greater than of cast or ductile iron, which means that thermal expansion has to be accommodated in long continuous lengths of pipe where high temperature differentials are likely.

Pipe Deterioration Mechanisms and Failures

The deterioration of pipes may be classified into two categories. The first is structural deterioration, which diminishes the structural resiliency of pipes and their ability to withstand the various types of stresses imposed upon them. The second is the deterioration on the inner surfaces of the pipes resulting in diminished hydraulic capacity, degradation of water quality and reduced structural resiliency especially in cases of severe internal corrosion. In the following discussions the focus is on exterior deterioration, as it is the principal contributor to structural failure of pipes.

Table 1. Mechanical and thermal properties of pipe materials.

	Cast iron		Ductile iron	Asbestos cement	PVC	HDPE
	pit	spun				
Elastic modulus, GPa	120	137	165	20-25	2.25	0.69
Ultimate tensile strength, MPa	173	250	290	25	48	22
Strain to failure, %	0.5	0.5	7	1	10	10
Poisson’s ratio	0.30	0.30	0.28	0.3	0.42	0.45
Thermal coefficient, $\times 10^{-6}/^{o}C$	12	12	11	8.5	79	220

The predominant deterioration mechanism of the exterior of cast and ductile pipes is electro-chemical corrosion with the damage occurring in the form of corrosion pits. Conditions that promote electro-chemical corrosion include aggressive soil conditions such as moisture content, chemical and microbiological content, electrical resistivity, aeration, redox potential, use of dissimilar metals, stray electric currents due to electrical grounding or other sources of direct currents. Under extreme conditions, corrosion can impact pipe integrity as early as 5 years after installation. The damage to grey cast iron is often disguised by the presence of “graphitisation”, which is a term used to describe the network of graphite flakes that remain behind after the iron in the pipe has been leached away by corrosion. Either form of metal loss represents a corrosion pit that will grow with time, and eventually lead to a break. The interior of a metal pipe may be subject to tuberculation, erosion and crevice corrosion resulting in a reduced effective inside diameter, as well as a breeding ground for bacteria. Severe internal corrosion may also impact pipe structural strength. The supply water affects the internal corrosion in pipes through its chemical properties, e.g., pH, dissolved oxygen, free chlorine residual, alkalinity, etc., as well as temperature and microbiological activity.

The long-term deterioration mechanisms in PVC pipes are not well documented mainly because these mechanisms are typically slower than in metallic pipes and also because PVC pipes have been used commercially only in the last 35 to 40 years. However, these deterioration mechanisms may include chemical and mechanical degradation, oxidation and biodegradation of plasticisers and solvents (Dorn *et al*. 1996).

Asbestos-cement and concrete pipes are subject to deterioration due to various chemical processes that either leach out the cement material or penetrate the concrete to form products that weaken the cement matrix. Principal ingredients of asbestos cement and concrete pipes are tricalcium silicate (Ca_3SiO_5), dicalcium silicate (Ca_2SiO_4), tricalcium aluminate ($Ca_3Al_2O_6$) and calcium hydroxide ($Ca(OH)_2$). The cement salts (silicates and the aluminate) hydrate when in contact with water to produce calcium hydroxide.

Calcium hydroxide in contact with water leaches in the form of Ca^{+2} and OH^- with a resulting reduction (material softening) in pipe strength (Slaats *et al*., 2004; De Silva *et al*., 2002). The presence of inorganic or organic acids, alkalis or sulphates in the soil is directly responsible for concrete corrosion.

In reinforced and prestressed concrete pipes, low pH values in the soil may lower the pH of the cement mortar to a point where corrosion of the prestressing or reinforcing wires occurs, resulting in substantial weakening of the pipe (Dorn *et al*. 1996). The damage to PCCP pipe initiates with the formation of cracks in the external mortar coating enabling chloride and sulphide ions to reach the prestressed steel wire through diffusion. As corrosion products develop, the external mortar coating delaminates, which further increases the exposure of the wires to the aggressive environment. The number of steel wires that corrode and break increases with time, leading to eventual pipe failure when a sufficient number of wires break and the design factor of safety is compromised.

Inspection Technologies

Over the past 10 to 12 years several non-destructive technologies (NDT) have been developed to inspect water pipes. Some of these technologies exploit the specific pipe material properties and consequently they are not applicable to all pipe materials. Water supply operators prefer not to interrupt water supply for inspection to avoid customer complaints (public trust). The disturbance of internal tuberculation can lead to increased red water complaints, sloughing off tuberculation that clogs graphitised areas in cast iron pipes, extra effort required for disinfection after inspection, increased risk of contaminant intrusion, etc. These utility requirements call for “non-intrusive” NDE or NI-NDE.

The risk management approach for buried pipelines is relatively novel in the water industry. Different terminology has cropped up in the course of developing risk management strategies and inspection technologies. It is therefore important to establish consistent terminology so that the same terms mean the same things to all in the water industry. Schematic representation of all the principal events that take place in the management of buried pipelines are shown in Fig. 6. Inspection is primarily carried out to identify distress indicators and is a prelude to establishing condition state(s). It is also important to note that this review is limited to discussion of the detection of structural distress indicators by readily or nearly available commercial technologies but does not include a discussion on the interpretation of various distress indicators into condition state(s).

In the ensuing discussions, each applicable technology is described in terms of basic principles and how they apply to specific pipe materials. Dingus *et al*. (2002), Makar and Chagnon (2001) and others have recently reviewed the available technologies. Some of these technologies (Table 2) are available commercially while others are experimental and have been tested only on demonstration projects. Leak detection technologies are not addressed here.

Table 2. Summary of NDE technologies applicable to different pipe materials.

NDE method for structural defects	**AC**	**Concrete**	**Ductile/ cast iron**	**Steel**	**PVC/PE**	**Availability for water/other pipes**	**Dewatering requirement**
Visual (direct/remote)	√; LC	√; LC	**?**; HC	**?**; HC	**?**; LC	yes/yes	not necessary
RFEC	×	**?**	√; MC	√; MC	×	yes/yes	not necessary
RFEC/TC	×	×	×	×	×	yes/no	no
Magnetic flux leakage	×	×	**?**; HC	**?**; HC	×	R&D/yes	not necessary
Ultrasonic	**?**	×	√; M/HC	√; M/HC	**?**; LC	R&D/yes	not necessary
Impact echo (IE)	√; LC	√; LC	×	×	×	yes/yes	no
Georadar	√; NC	**?**	**?**	**?**	**?**	yes/no	no

× : not applicable; √: available; **?**: may/may not work;

Cleaning requirements: LC: light; MC: moderate; HC: heavy; NC: none

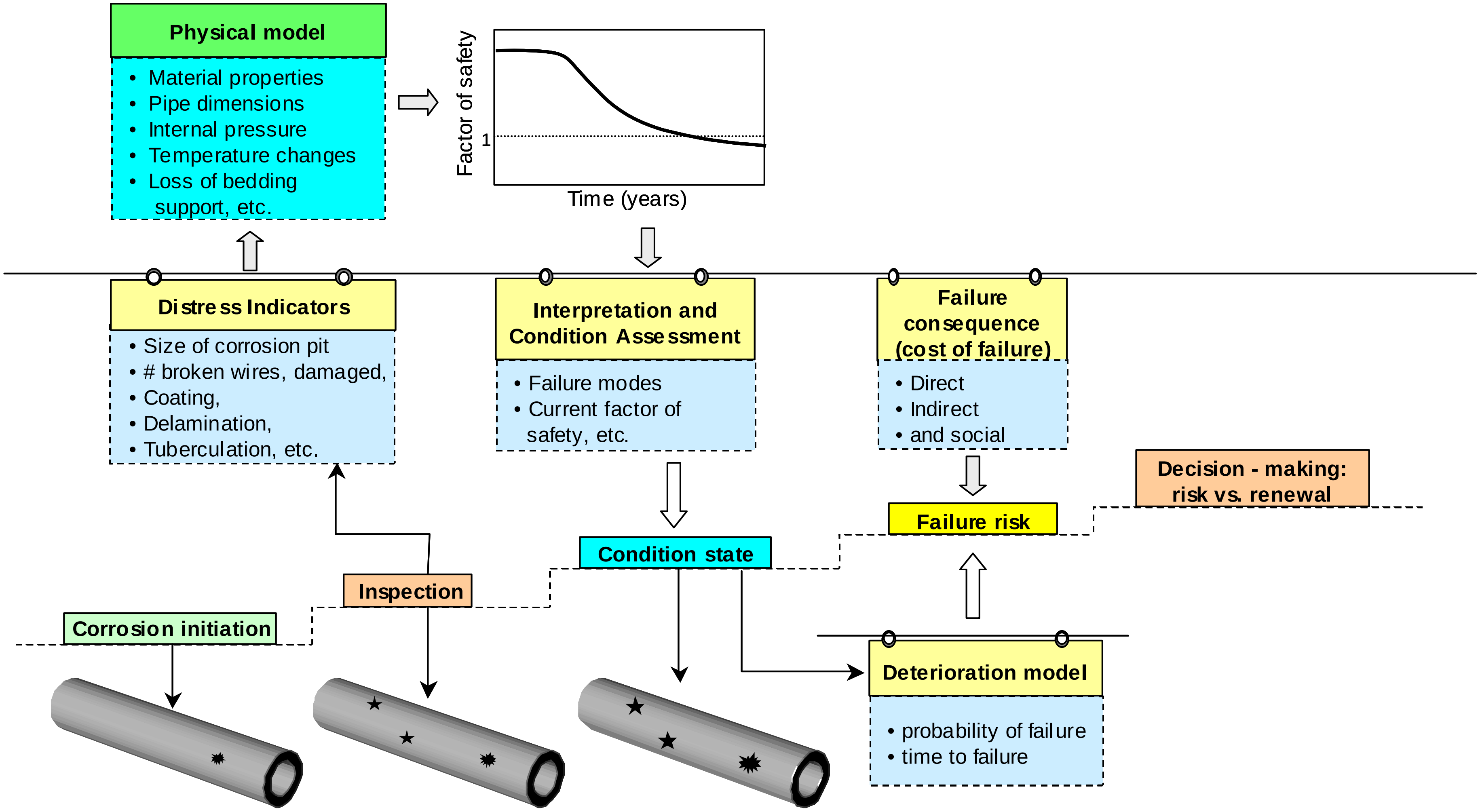

Fig. 6 Schematic for inspection, condition assessment, and failure risk evaluation of pipes.

Magnetic flux leakage (MFL) could be applicable to metallic pipes and it has been developed commercially only for oil and gas pipes, not for water pipes, likely because the magnets have to be in close contact with the pipe wall, which is difficult to achieve in tuberculated water pipes. Consequently, further discussion on MFL is not pursued here.

Visual inspections

Principle: Visual inspection is the simplest NDE technique and is often overlooked as a prelude to any subsequent inspections. Modern cameras equipped with fibre optics provide high quality images even in poor lighting conditions. Commercial equipment is readily available since its use has become routine for sewer inspections.

Pros and cons: Cameras mounted on remotely operated vehicles (ROV) provide access to small diameter pipes that are inaccessible to humans. Observations are at best qualitative and will only give information on the distress indicators visible on the inside pipe surface. However, transcription of camera observations to data can be time consuming. Some recent research effort has been directed towards automating this process, especially for sewers. Its application is inappropriate in lined or unlined metallic pipes with tuberculation pipe since the inside pipe surface is occulted. The principal advantage is that good quality cameras are now commercially available. Pipe dewatering is not essential if the water within the pipe has no sediments or significant turbidity.

Remote eddy field current (RFEC)

Principle: Remote field eddy current (RFEC) method is based on measurement of the attenuation and phase delay of an electromagnetic signal as it passes (Fig. 7) through the wall thickness of a metallic pipe. A typical set up consists of a exciter coil that generates a direct (internal) electromagnetic field that travels inside the pipe but its strength attenuates rapidly because of circumferential eddy currents induced in the conducting pipe wall. Simultaneously, the exciter generates another indirect (external) field that travels through the pipe wall with minor attenuation (Staples, 1996). Changes in field strength and attenuation are dependent on pipe wall thickness and thus the signature of these changes enables the determination of pipe wall thickness. In practice the introduction of the equipment in the pipe is through the fire hydrant. Roubal (2003) describes a variation on the application of eddy current that is frequency independent (broadband electromagnetics-BEM). Thus, it allows the possibility of adjusting the operating frequency to suit specific pipe materials and sizes.

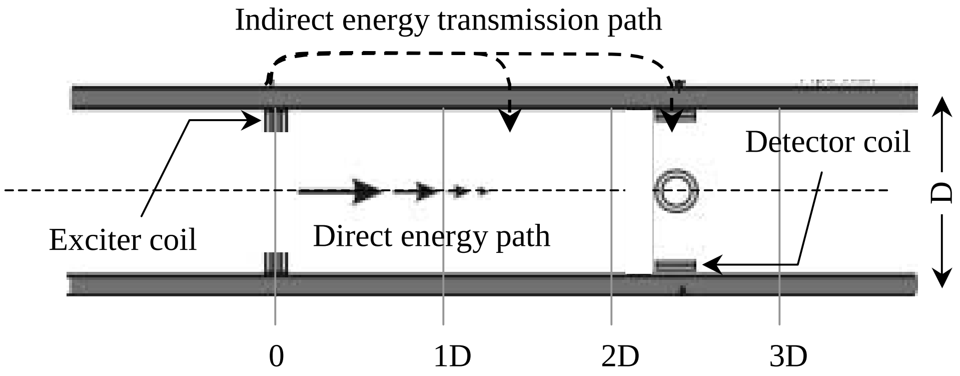

Fig. 7 Remote field eddy current (RFEC) in metallic pipe.

Pros and cons: The technique is only suitable for metallic pipes such as ductile and cast iron but not for asbestos cement pipes. The pipes require cleaning before inspection to ensure that the equipment can travel freely without encountering encumbrances. However, as discussed earlier, water utilities sometimes prefer not to scrub off tuberculation as it increases the likelihood of water main leaks as well as red water complaints. Most commercially available equipment is articulated and can only be used for small diameter mains (150 mm (6”) to 250 mm (10”) and is unavailable for large diameter mains where inspection is most justified economically, as discussed earlier. Close contact between the exciter and detector coils and pipe wall is not essential and therefore thorough cleaning is not required. The technology can be used in both unlined and cement lined pipes. The RFEC inspection technique is not likely to identify small pits and each set of equipment has to be calibrated independently. It is also important to note that although RFEC can identify the axial pit location, most current commercial tools are unable to locate its position circumferentially.

Available equipment (Roubal, 2003) based on broadband electromagnetics is able to inspection pipes of any size but only straight or near straight pipes and is unable to negotiate sharp bends. The inspection rate slows down as pipe sizes increase due to the large amounts of data generated. Other advantages of the equipment based on broadband electromagnetics are: the presence of external coating or internal liners does not hinder inspection of the ferrous part of the pipe, detects cracks, corrosion pits or graphitised zones.

Remote eddy field current/transformer coupling (RFEC/TC)

Principle: A technique based on remote eddy field current/transformer coupling (RFEC/TC) (Mergelas and Kong, 2001) is specifically designed for prestressed concrete cylinder pipes (PCCP), where the spirally wound prestressed steel wires act as a solenoid when electromagnetically excited (Fig. 8). The RFEC field dominates as explained above in the presence of the steel cylinder but the spiral wires interact with the RFEC field to create a transformer coupling effect. Experimental evidence shows that the transformer-coupling component is the dominant response but it diminishes as the number of broken wires increases.

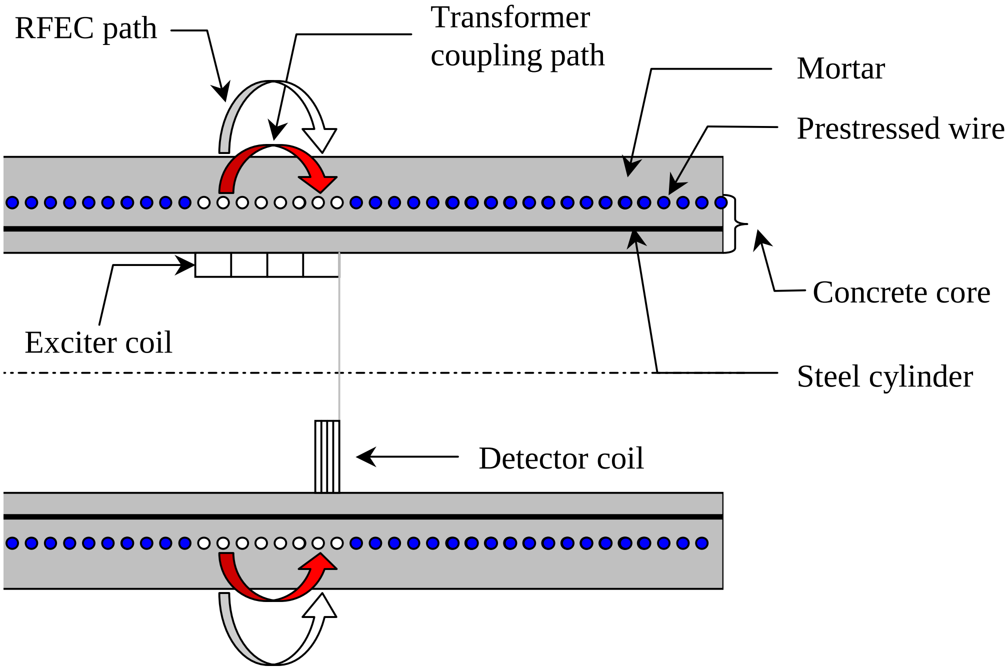

Fig. 8 Remote field eddy current/transformer coupling (RFEC/TC) in metallic pipe.

Pros and cons: The technique is only suitable for the inspection of PCCP pipes of a size that are accessible to humans. Available commercial equipment can only be used in pipes that are dewatered. Delaminations of external mortar coating or internal lining cannot be detected except that they can be assumed to have occurred if a sufficient number of prestressed wires have broken.

Ultrasonics

Principle: The ultrasound method is based on the measurement of transit times for sound waves to travel through the pipe walls and back (Fig. 9) and from acoustic properties of the materials. Theoretically, the pipes can consist of different materials, e.g., cement lining, but as long as there is good contact at the interface between the materials. A typical set up consists of a piezoelectric sensor that generates an ultrasonic pulse and measures the travel time between the sensor and pipe wall. The couplant, e.g., grease, between the sensor and pipe wall is required to ensure that the ultrasound waves impinge on the pipe wall since air is a poor transmitter of sound waves.

Pros and cons: The technique is most suitable for metallic pipes such as ductile and cast iron but is not suitable for asbestos cement pipes as the acoustic waves are likely to attenuate significantly in a deteriorated (softened material) pipe. The internal pipe wall has to be very clean so that all materials between the sensor and pipe wall have known and well-defined acoustic properties. Moreover, irregular profiles of tuberculation make it difficult to transmit ultrasonic waves, which are likely to scatter and attenuate rapidly through the much softer tubercles, and thus making it difficult to detect and conduct signal processing of the reflected waves. Of course water is an obvious couplant. However, as discussed earlier, water utilities are sometimes resistant to scrub off tuberculation. The ultrasonic technique can theoretically detect 3D geometry of corrosion pits, voids and cracks. Most commercial equipment is only available for oil and gas pipelines.

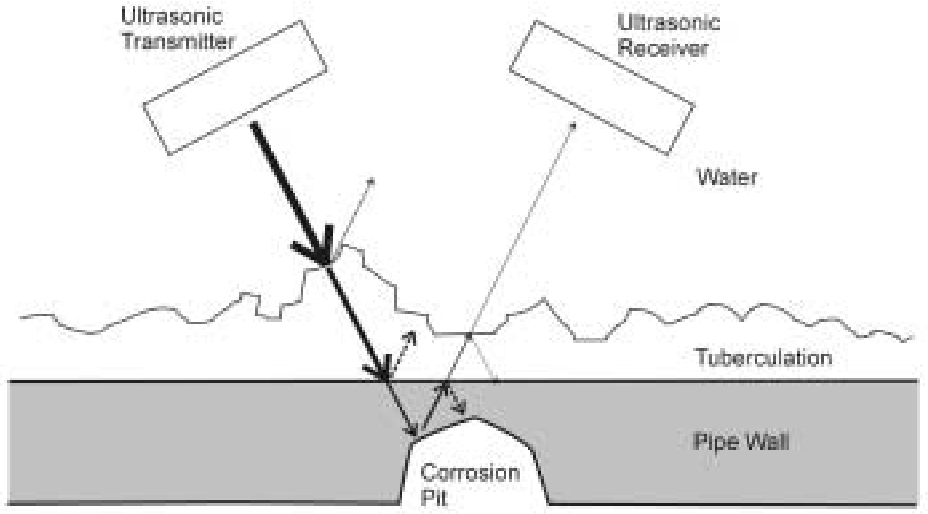

Fig. 9 Ultrasonic arrangement in metallic pipe.

Impact echo (IE)

Principle: Impact echo (IE) tests involve listening or analysis of acoustic waves generated as a consequence of a solid object (hammer, rod, etc) striking (impacting) the pipe wall. A firm or high frequency sound typically signifies no pipe wall deterioration while a hollow or low frequency sound can occur because of deteriorated or delaminated pipe wall. The simplest application is manual tapping of inner or outer (if accessible) pipe walls and identifying deteriorated dud zones. A more complex application of impact echo consists of instrumented hammers that impart impulses of a known force and specific duration. Reflected pulses are detected by appropriate transducers and analyzed to determine wall thickness and the presence of delaminations.

Pros and cons: While the technique is also suitable for metallic pipes such as cast and ductile iron it has been used mostly for non-metallic pipes such as PCCP and asbestos cement pipes. The pipes need not be dewatered for impact echo to function but the internal pipe walls has to be fairly clean. The presence of tuberculation in unlined cast or ductile mains will make impact echo dysfunctional because acoustic properties of tuberculation will likely attenuate the sound waves significantly. The impact echo technique detects the presence of corrosion pits, voids and cracks but not their extent. The

Washington Suburban Sanitary Commission (Woodcock and Holt, 1966) has developed equipment based on the principles discussed here for application to PCCP but commercial equipment is not yet available.

Georadar

Principle: Georadar technique is based on measurement of transit time and signal strength attenuation of electromagnetic impulses as they travel through a pipe wall thickness (Fig. 10). The technique is most applicable to asbestos cement pipes where the deterioration is often in the form of soft layers either on the outside or inside of the pipe or both. The thickness of each layer is determined from travel times and signal strength as well as the electrical properties of various layers. The technique was developed in the Netherlands and Australia where it has been used extensively for sewerage pipes and has recently (Slaats *et al*., 2004, De Silva *et al*., 2002) undergone tests for its applicability to asbestos cement water mains.

Pros and cons: The technique is suitable for non-metallic pipes such as asbestos cement pipes. Under present arrangements the pipes can only be inspected externally which means that pipes need to be uncovered at specific locations and hence cannot be inspected continuously over long stretches. On the other hand, the technique does not require interruption of the water supply.

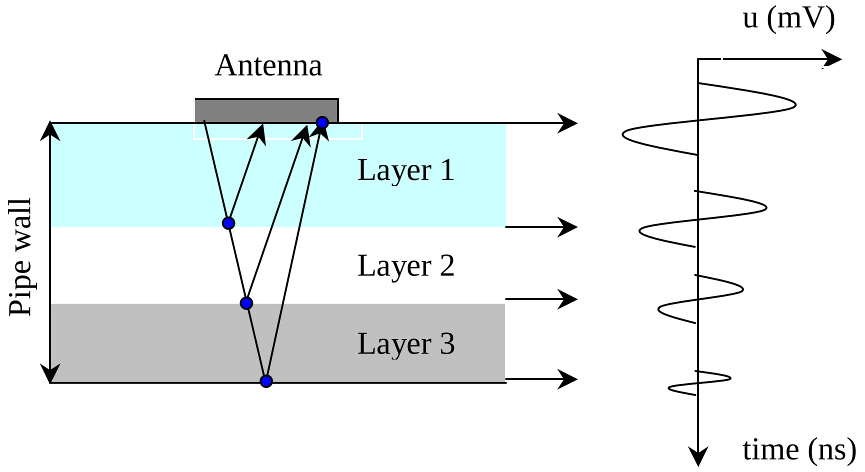

Fig. 10 Georadar arrangement in asbestos cement pipe.

SUMMARY AND CONCLUSIONS

As NDE techniques evolve and include the development of various types of sensors and robots, it appears that failure anticipation and prevention is likely to become more technologically feasible as well as affordable. Currently, it seems that only mains prone to high-cost failure (namely transmission mains) can justify these techniques, but over time this will likely change. In the meantime, while the bulk of water distribution networks are comprised of small mains with relatively low failure consequence, NDE techniques can, in some circumstances, complement empirical models, which rely on historical break records.

Over the past 10 to 12 years significant progress has been made in the inspection of water pipelines to detect structural distress indicators. While most of inspection techniques developed are based on non-destructive (NDT) methods, none as yet are able to inspect pipes with tuberculation without significant cleaning. Expectation that the application of any single NDE technique will identify all the distress indicators is probably unrealistic and hence an attempt to combine technologies may be appropriate.

Water utilities still do not inspect enough of the their pipe inventory at regular frequencies in spite of available technologies. Operators of drinking water supply systems are risk averse and hence technology developments are closely scrutinized before their adaptation primarily because of health and safety concerns, e.g., pressure drop can likely lead to intrusion through deteriorated pipes, and disinfection of pipes after inspection. However, it is important that water utilities take a proactive stand on the management of their ageing water supply systems, in order to maintain modern sustainable communities. Recent reporting requirements introduced by the US Government Accounting Standards Board (GASB), known as GASB Statement 34, may provide the impetus for water utilities to inspect their pipelines. GASB Statement 34 requires that all state and local governments will have to identify and value their assets and periodically acknowledge the state of their physical condition (Sanford Bernhardt, 2000).

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