LIFE CYCLE ANALYSIS OF WATER NETWORKS

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ABSTRACT

Water authorities around the world are faced with the problem of ageing distribution networks and often only limited historical data on which to base a sound long term, cost efficient replacement policy. The LICAN approach to whole of life costing is introduced and a hypothetical case study is used to demonstrate the importance of such an approach. A selection of pipe networks utilizing different pipe materials (PVC, DI and PE) are modeled to determine their whole of life cost, taking into account installation, maintenance and repair costs.

Keywords: water distribution pipes, polyethylene, uPVC, ductile iron, life cycle cost of pipe

INTRODUCTION

Water authorities around the world are faced with the problem of ageing networks and often only limited historical data on which to base a sound long term, cost efficient replacement policy. Water distribution pipe networks last for decades and thus it is essential to base any replacement strategy on a life cycle basis, rather than possible short-term benefits, such as the pipe's initial cost. However, assessing the life cycle benefits of alternative pipe type networks usually relies on detailed analysis of a utility's existing system and many do not have the necessary data, time or indeed resources to enable such a study. A simple yet effective method for carrying out long-term life cycle analysis is required for these utilities.

WHOLE OF LIFE COSTING

The concepts of life cycle costing or whole of life costing have been well understood for many years (1, 2) and have been practiced by a many companies worldwide who are responsible for a variety of assets including buildings and utility networks. For a water network the whole of life costs are the costs of acquiring it (including consultancy, design and construction costs, and equipment), the costs of operating it and the costs of maintaining it over its whole life through to its disposal - that is, the total ownership costs. These costs include internal resources and management overheads; they also include risk allowances as required; flexibility (predicted alterations for known change in business requirements, for example), refurbishment costs and the costs relating to sustainability and health and safety aspects (3). Countries like Australia, New Zealand and the United Kingdom are leading the world in the implementation of such a management approach (4), but the United States is lagging behind which has the potential to lead to poor decisions being made about infrastructure renewal.

The American Public Works Association has noted that it is essential that the industry move from a low bid procurement strategy to a life cycle costing strategy (5). They also note that currently within the United States, most public infrastructure is constructed through some form of low-bid procurement system that does not necessarily produce the most effective or efficient system when the totality of maintenance, repair, and rehabilitation are considered.

Many, if not most, federal, state, and local procurement regulations are cumbersome or outright barriers to implementing a procurement analysis on a life cycle costing basis. They conclude by saying that much of the resistance to life cycle costing comes from elected and appointed officials that have a short-term perspective that is measured in a fraction of the useful life of the asset (5). To overcome this short-term view it is essential that simple and effective tools are available that demonstrate the benefits of whole of life costing.

ESTIMATING PIPE FAILURE

The essential part of any life cycle analysis for water networks is accurately estimating the life time performance of the pipes that make up the network, including their expected failures, repairs and eventual replacement and the associated costs (both direct and indirect) for each stage. A number of planning models are currently available to allow the future costs of pipeline failures to be assessed for water reticulation networks, such as KANEW (6) developed under AwwaRF funding and PARMS-Planning developed by CSIRO (7). However, these models require detailed analysis of the failure data for all pipe assets, and some require specific failure curves for each class.

If a water authority has a database of recorded failures, it can be used in the development of statistical failure models. However databases on pipe failure statistics are often incomplete and/or limited to a short time period and in many cases it is difficult to ascertain whether a failure resulted in a repair or replacement or if the pipe was replaced at the end of its economic life. Also, the statistical models developed from this failure data, in practical use, assume that the pipe system is in a steady state, which means that all outliers and transients have to be removed from the database before estimation begins.

Consequently future pipe failures are estimated from failure data contained in the failure databases, subject to cleansing and manipulation, or by utilizing the known material and operating characteristics to develop physical failure models. Regardless of the method used there is a certain level of uncertainty in each of these models because of unknown or uncertain data and one has to determine whether the level of uncertainty is low enough to enable use of these models.

PIPE FAILURE DATA

As stated above, many authorities have data sets that are incomplete or only cover very limited time periods, making analysis difficult. In some cases, although authorities have been collecting data it has been inconsistent, not detailed enough or simply the wrong type of data. Data collection is an essential part of any water authority's activities, but careful planning is required to determine what data should be collected, how it should be collected and how it should be stored.

Data for pipe failure analysis relies on accurate and consistent data over several years (usually at least five years) to achieve meaningful predictions of future trends. The type of data required will include:

- Pipe material – using industry agreed codes (American Water Works Association - AWWA) pipe classification).
- Date installed – provide year of installation (month and day are usually not critical).
- Pipe location – the suburb, town or zip code is required and also what the pipe is actually buried under (road, footpath, verge, etc).
- Soil and topography data – again, use industry standard codes for this information.
- Failure data – when a failure occurs there is a set of data required including what type of failure was it (use industry standard codes or terminology), when did it occur (date and time are useful here) and what action was taken (pipe repaired or replaced).

Having in place good data protocols and ensuring that they are adhered to will greatly aid future analysis projects. Discussing with analysts what their data requirements are will often avoid common practices such as reusing unique identification codes for pipes that have been replaced or discarding data on abandoned or replaced pipes which may seem efficient, but can cause frustration during analysis.

STATISTICAL AND PHYSICAL MODELS

Statisticians model the failure processes on a level above the physical level, where the probability of failure is derived from a logistic regression based on attributes of the pipe, its environment and handling. Many independent records on actual failures are required for successful statistical estimation. It also means that as more explanatory variables are used, the number observations needed increases.

In lifetime models, care has to be taken in differentiating between economic (including financial decisions) and physical lifetime. The end of the economic life for a pipe is normally defined as the point of time when the present value of the future repair costs exceeds the current replacement cost. To estimate the remaining physical lifetime of a pipe, its material properties have to be measured at various time intervals for stress, pit depth, etc. The deterioration process can then be estimated via regression and the time to critical burst conditions predicted.

Physical models (sometime known as mechanistic models) have mainly focused on the deterioration of the pipes, particularly for corrosion. With plastics pipes, as availability of failure data is limited, application of statistical models is difficult. Engineers can describe the physical processes in an individual pipe to predict breaks and perforations of the materials under study. This is the only method available for estimating the remaining lifetime of large pipes, which frequently have no burst observations. Most of the physical models are, according to the structural mechanics tradition, deterministic (8, 9).

THE LICAN APPROACH

In response to the lack of simple whole of life tools available for the water industry within the United States, the Plastics Pipe Institute sponsored the development of the LICAN (LIfe cycle Cost Analysis of Networks) system. The Australian based Commonwealth Scientific and Industrial Research Organisation (CSIRO) undertook the research and designed LICAN to be a simple computer–based model that illustrates the impact of selecting alternative materials for municipal pipes on the total cost over their whole life. It utilizes a fixed set of alternative scenarios determined by LICAN and focused on size of the system and the material of the pipes and is based on a failure rate model for each of the pipe materials to enable users to compare anticipated life-cycle costs of different piping solutions. Users need to provide the costs of installation, repair and replacement of pipes in the network for pipes of varying sizes and set a time frame for analysis. LICAN includes the cost of water loss, but excludes the cost of failure due to third party damage as this affects all materials uniformly. Outputs include tables and charts of comparing alternatives, time based changes, growth patterns and network characteristics, summaries of pipe materials by length and size for each system size, initial cost of piping system (including material cost and construction cost) for each system size and pipe material and annual maintenance cost (for each year of the time analysis window) for each system size and pipe material.

The overall approach to the LICAN model was to forecast the expected annual probability of failure for each type and size of pipe for the next one hundred years, based on the age and other characteristics such as the material and length of each pipe. For each pipe segment, the expected probability of failure of every pipe is estimated for each year in the forecast period.

The inventory of the actual pipe network enables the full network performance to be obtained from relatively simple models of performance based on only a few parameters.

The costs of maintenance are provided per repair and the cost of replacement pipes are calculated from costs per unit length. Replacements reduce the length of existing pipes and create a new pipe in the year of replacement. All failures are repaired. Whether a pipe is replaced in any particular year is determined by comparing the economic consequences of retaining and maintaining the pipe into the future as it fails with the cost of renewing it and replacing it if the latter is cheaper. The faster failing pipes are of more importance (particularly for customer satisfaction) than the average or long lived pipes.

LICAN does not model all the potential consequences of a pipe failure, such as penalty payments to customers, traffic disruption and other costs that utilities may encounter when a pipe fails and these would need to be examined on a case by case basis based on local conditions.

LIFE CYCLE COST PREDICTION

The LICAN model calculates potential future costs for the collection of pipe assets over a defined forecast period (typically one hundred years). The model predicts failures and interruptions on a year by year basis, replaces any selected pipe assets, and then moves on to the next year in the forecast period and repeats the process on the updated asset set.

The cost calculations include:

- Installation cost – During the first few years of the planning period assets are added to the network as the system grows. The cost per foot associated with the new material and diameter is multiplied by the length to give the installation cost for the asset. The LICAN program adds pipes assets one at a time for each material/diameter/length combination. If the growth rate is not yet achieved, then the next combination with assets still to be installed is considered.
- Repair cost – The specified cost of a repair event plus any length replaced. The event cost is multiplied by the fractional number of repair events expected in the given year to generate the total repair cost for the asset for the given year.
- Leakage cost - The model calculates background leakage from joints. The volume of water lost by the asset is then multiplied by the unit leakage cost (per 1000 gallons) to determine the leakage cost.
- Replacement cost – An asset is replaced when the prediction of the total discounted repair costs for the asset is greater than the cost of replacing the asset and experiencing a (presumed) lower rate of failures (and repairs) into the future. The period for which these calculations are done is entered in the program as the "discounting time span". If in a given year the asset is not replaced, then the replacement cost will be zero.

Costs which are not part of the model include:

- Pumping cost and hydraulic efficiency - The pipe network is designed as a gravity network, with pumping limited to topping up supply tanks, and so these costs would be similar for all networks.
- Corrosion cost - The effects of corrosion are included in the pipe failure models.
- Customer service rebates and penalties due to failures.

NETWORK DESIGN

Hypothetical water supply networks for five different sized cities, incorporating the use of different types of contemporary pipe material, have been designed and hydraulically analyzed to produce a particular set of pipe, hydrant, gate valve and water service tap inventories that may be used as a database for developing a whole of life water supply distribution system cost model. Each set of design assumptions, system configurations and topographic conditions assumed for a study of this type will of course lead to different sets of results being produced. However, the processes of analysis and design assumptions adopted in this study are believed to be rational and robust and the pipe databases generated are believed to be representative in terms of the relative pipe cost and determined sizes.

The following five city sizes were adopted: 5,000, 50,000, 100,000, 200,000 and 400,000 connections. The methodology and system parameters are intended to produce a representative set of idealized water supply networks using a limited set of generalized design parameters and a relatively simple design approach.

Each of the hypothetical water supply distribution systems analyzed supplies a “typical” mix of land uses, which can be considered representative of urban cities. The analyses are based on a specified set of “typical” design parameters related to:

- The “representative” mix of land uses within the supply zone.
- Typical average day, maximum day, maximum hour and fire demands.
- Typical maximum and minimum residual supply pressures adopted within networks. The maximum residual pressure within each distribution system is limited to 100 psi (690 kPa). The maximum sustained working pressure within the pipes, after allowing for the depth of burial, is approximately 104 psi (718 kPa).
- Network geometry and size, supply zone topography and the hydraulic characteristics of the pipe materials used.

An analysis was done for each combination of material and city size. This involved an optimization process which varied the pipe diameters assigned to each length of pipe from amongst the allowable diameters. The lowest cost network found, which met the specified design criteria, was selected and the inventory of pipes was extracted.

FAILURE RATE VERSES AGE CURVES

In the LICAN model separate failure rate curves were determined for each individual pipe in the network. The LICAN model considers three pipe materials –Polyvinylchloride (PVC), Ductile Iron cement lined (DI/DICL) and Polyethylene (PE), and a mixed network which contains equal lengths of all three. However, because of the lack of published failure data available on these materials (especially PE and PVC), statistical models would not give a valid representation of future failures; consequently only physical failure models were utilized. Since physical failure models do not take account of premature failure due to poor installation, LICAN does not make any allowance for this type of event.

A physical probabilistic failure model was used for fracture failures in PVC pipes, which combines fracture mechanics theory with Monte Carlo simulation methods (10, 11). For a set of prescribed loading conditions, fracture mechanics theory was used to predict slow crack growth and eventual brittle fracture failure from inherent defects in the pipe wall. As part of a separate study the fracture properties of PVC pipes manufactured in North America were determined for input into the model (12). A typical set of failure rate verses age curves for fractures in PVC pipe is shown in Fig. 1.

As shown, failure rates estimated from the physical probabilistic model are predicted to initially increase sharply, then slow for an extended period as the pipe ages. As expected the effect of pressure is to increase operating loads and produce a corresponding increase in average failure rate. For this particular simulation long term failure rates increased from approximately 1 per 100km/per year (1/62mi/year) to 6 per 100km/per year as pressure increased from 105 psi to 123 psi.

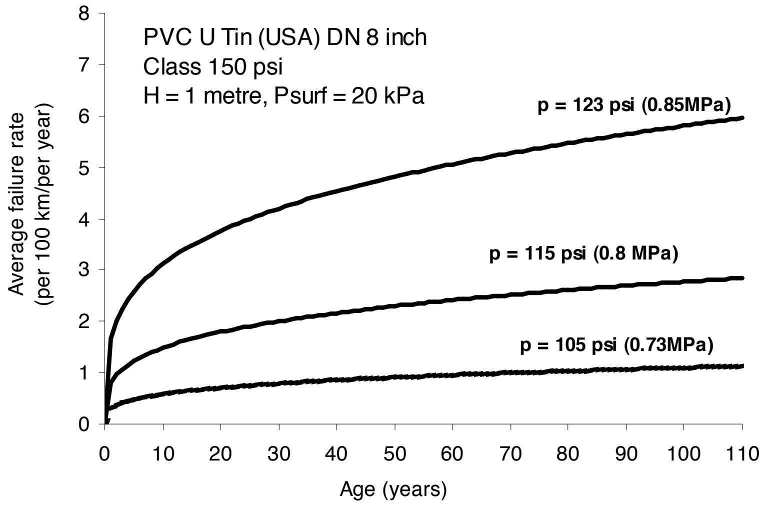

Fig. 1 Typical failure rate verses age curves for fracture failures in US PVC pipes (Burn et al, 2005)

In addition to the fracture failure model for PVC pipes, a simple statistical model to forecast rates of non-fracture failures (i.e. joint and fitting failures) was also developed. In the absence of historical failure data from US water utilities[1], the UK Water Industry Research (UKWIR) national mains failure database was used to generate this simple model. The UKWIR database contains descriptions of pipe attributes and installation years for different materials, together with descriptions of individual pipe failures (13). It should be noted that the UKWIR database may tend to provide conservative estimates for the failure rates of certain materials when applied to the US context where water pressure and pressure surges are considered to be higher. This is because failures in some materials, such as PVC, are often considered to be pressure related (10, 11).

An algorithm was written to extract non-fracture failures in PVC pipes from the UKWIR database and generate failure rate verses age curves. An example of failure rate verses age data (for joints and fittings) extracted from the UKWIR database is shown in Fig. 2.

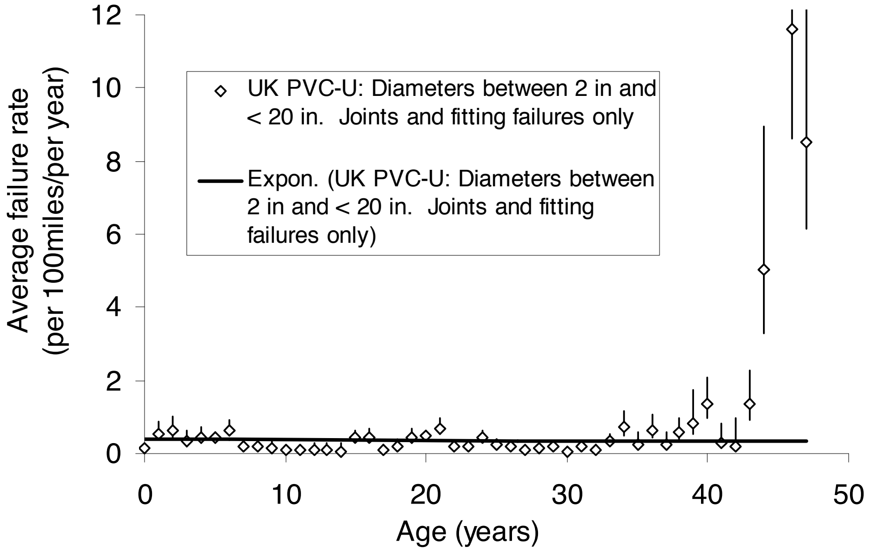

Fig. 2 Failure rate verses age data for joints and fittings –(from UKWIR database)

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[1] An extensive survey resulted in anecdotal evidence of utility experiences with PVC, but not quantitative failure data

In the absence of a physical failure model for PE and DICL pipes, data from the UKWIR database was also used to generate failure rate vs. age curves for these pipe materials. This resulted in failure rates for PE being around 3.2 failures/100km/year (2.0 failures/100mi/year) and DICL around 20 failures/100km/year (12.4 failures/100mi/year). The use of UK based data for DICL pipes may mean that the performance is better than experienced in the northern parts of the US and Canada as the freeze/thaw cycle, which can shorten the life expectancy of DICL pipes, is not taken into account. In addition, a higher proportion of corrosive soils in the US would also impact negatively on the performance of DICL and consequently, the failure rates for DICL are considered conservative.

LEAKAGE COSTS

Loss of water through leaks represents a significant cost for many networks that is often overlooked. Leakage costs have been estimated through a leakage model that considers total leakage as the combined leakage from:

- Background leakage, which occurs mainly through joints in the pipes and perforations.
- Leakage from burst failures.

The costs of leakage are included in the cost tables as a single dollar value per unit loss. The costs account for background leakage and losses from burst failures such as longitudinal splits and circumferential breaks.

Temporal deterioration of DICL, PVC and PE pipe systems were considered in the development of leakage algorithms. Although the action of aggressive soil environments differ on different pipe types, the effects on PVC and PE pipe itself will not be significant. However, if unprotected, DI pipe will deteriorate in aggressive soils or if protection is breached through poor installation practices or third party damage. A Canadian study covering 1129 miles of PVC pipe and 2632 miles of DI pipe indicated that the average joint failure rates were 0.35/100miles/year and 0.42/100miles/year, for PVC and DI pipes respectively (14). In contrast, average failure rates associated with hole/corrosion pitting failures were 0/100miles/year and 11.8/100miles/year for PVC and DI respectively. Assuming that these pipes were installed according to normal industry practice, the Canadian data suggests that as age increases, DI pipes are more susceptible to deterioration than PVC pipes.

PE systems are less susceptible to temporal deterioration as they have fully welded jointing systems. These systems are not expected to show significant deterioration as there are no components that can be displaced through soil movement or corrode from aggressive soil environments.

BACKGROUND LEAKAGE

Background leakage occurs from small leaks at joints between pipe lengths and at property connections (15). Separate leakage algorithms are given for sections of pipeline with and without property connections.

For sections of pipeline without property connections, the AWWA models for maximum allowable leakage during hydrostatic testing AWWA M23 for PVC (16) and AWWA M41 for DI (17) were adopted, the latter with modifications to factor in effects of ageing. In the absence of published data the estimation of leakage rates for older pipes was based on the reported leakage rates from a water supply network in an Australian city. Consequently, a 50% increase of the maximum allowable leakage is assumed for DI systems to account for corrosion induced joint deterioration. A constant leakage rate is assumed for PVC, although some believe the PVC leakage is a reflection of pipe creep. The algorithms use half the maximum leakage allowed on the basis that the quality of workmanship will differ across a network. AWWA M55 for PE (18) advocates that leakage should be zero for PE pipe systems with fusion welded joints and on this basis the leakage in PE pipelines was assumed to be zero. Where these fusion welded joints are defective, the joint is likely to fail prematurely during testing and thus before commissioning.

BURST FAILURE LEAKAGE

International Water Association (IWA) studies have shown (15) that 95% of burst leakage events are reported, and on average the leakage losses from each event aggregates to $12m^3$/hour (53 gallons/minute) for 3 days at a nominal 500kPa (72psi) operating pressure before the leak is repaired. The remaining 5% of unreported bursts average losses per event of $6m^3$/hour (26 gallons/minute) (at 500kPa operating pressure) for 50 days before the repairs are effected. On this basis the losses from each reported and unreported burst failure event is $864m^3$ (228270 US Gal) and $7200m^3$ (1902245 US Gal) respectively at 500kPa operating pressure.

Unlike the case in background leaks, leakage rates from detectable leaks such as burst failures are sensitive to pipe material type (19) and different pressure correction factors apply for different pipe materials, which have been used by LICAN.

LICAN

LICAN is implemented as a Windows interactive program which requires minimal input, in terms of selecting options and specifying costs. It can display the results of its calculations as tables and graphs with the user able to interactively select what values to display. Options available include the entry of values that control the network growth rate, selecting the window for viewing of results, and defining the discounting period and discount rate.

To perform its calculations, LICAN needs installation costs, repair costs and replacement costs for the three pipe materials. It also requires a value for the cost of water that is lost via leakage from pipes. Installation costs are specified by initially choosing a particular pipe diameter, and entering the actual cost for such a pipe, then using a table of “standard” installation costs and rescaling them based on the supplied input, LICAN calculates installation costs for the other pipe diameters. Where required pipe sizes are larger than 20in in PVC networks, DI pipes are used, while the mixed network has equal lengths of all three materials.

Costing information was difficult to obtain and consequently indicative costs have been used, rather than actual costs. The “standard” installation costs along with the “typical” full cost for the supply and installation of pipes, fittings, fire hydrants and valves, including excavation and backfilling has been based on cost data taken from RS Means Heavy Construction Cost Data (20), but is presented here as relative cost differences, rather than actual dollar amounts.

CASE STUDY EXAMPLE

Fig. 3 shows the results from a typical simulation. In this case a medium sized network containing approximately 100,000 customers was selected and the total whole of life costs were modeled over 100 years. As the major focus for water utilities is the ongoing maintenance and replacement costs, all networks start as new pipe systems already installed, that is, initial installation costs have been excluded from this simulation. The simulation shows that the DI network has the highest cost by a considerable margin, followed by the mixed (DI/PVC/PE) network and the PVC/DI (DI for large pipes) network. The polyethylene network has the lowest cost/mile.

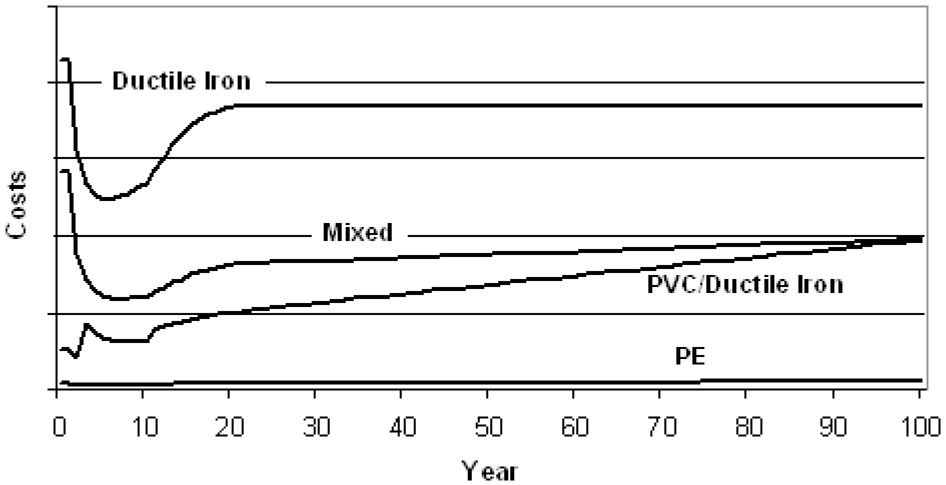

Fig. 3.Whole of life costing simulation (excluding installation costs) for a medium sized network[2]

The graph shows that the DI and the mixed (DI/PVC/PE) pipe networks experience a decrease in costs, before costs begin to increase again. Initial high costs in the first few years is due to high failure rate in the first few years of operation as they are more susceptible to installation related failures of pipes/joints. Once these pipes have been in the ground for several years, age once again begins to cause an increase in the failure rate and thus and increase in costs. Costs for these networks continue to rise over a 20 year period and then levels out. This represents the growth in the network, which for this example is set at 10% per year and is essentially complete after 25 years. The PVC (with DI for large pipes) network also has a more rapid rise in costs during the network growth period, but rather than flattening, costs continue to increase over the 100 year time period virtually drawing level with the mixed network cost level at the 100 year mark. The PE network, once the commissioning tests are completed, has nearly no increase in costs over the simulation period and the costs that do exist are significantly less.

The lower cost for the polyethylene network is due to two main reasons. Firstly, because its failure rate is low the cost per mile for repair/replacement is also low, even though the actual cost of repair and replacement work is similar to other pipe types. Keeping repairs to a minimum has significant benefits, as the model shows, repair costs generally represent 70% to 80% of the total costs experienced by a network. The second major benefit of PE networks is fusion-welded joints which ensure very low leakage rates and thus low water loss costs.

Changing network sizes can also have a dramatic impact on the costs associated with leakage. As network sizes decrease the number of joints per mile tends to increase and consequently the number of leaks per mile also increases. Fig. 4 shows the leakage costs for the first twenty years for a very small network (5000 customers). It can be seen that the DI and mixed (PVC/DI) networks have substantial costs associated with leakage for the first 10 years of the networks existence before stabilizing. Indeed, in these early years leakage costs for these networks represent up to 90% of the total costs. The mixed and PE networks have a relative flat leakage cost from year one onwards.

As network size is increased the impact of leakage is reduced significantly. For very large networks (400,000 customers) leakage costs for DI and PVC/DI start high, but rapidly

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[2] Mixed network comprises an equal mix of all three types of pipe material with hydraulic requirements averaged for the three separate material types. PVC/DI networks use DI pipes for diameters greater than 20 inches. (The installation cost of PVC pipes in these larger diameters exceeded the cost of comparable DI pipes.)

drop within the first few years by around 75%. For these very large networks, the majority of the costs are associated with repairs and not leakage

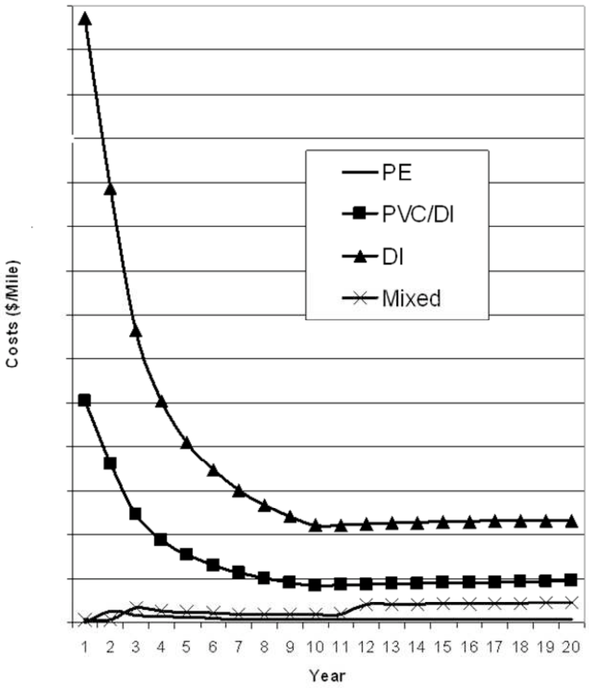

Fig. 4 Leakage cost simulation for a very small network

CONCLUSION

Whole of life analysis of water networks is essential for water utilities to undertake so that they can understand the true long-term costs of installing, maintaining and upgrading their assets. The United States preference to look strictly at lowest bid price could lead to serious consequences in the future with networks experiencing higher costs for repair and water loss and requiring faster renewal frequency of pipe installation as a result of the lowest upfront price approach.

The LICAN software shows that many of the contemporary pipe materials that are used, such as ductile iron and PVC may have significant long term cost implications. In contrast to PE pipe predictions, their relatively higher failure rate coupled with their higher leakage rates could result in significant maintenance costs and lost water costs over the lifetime of the pipe network. However, based upon available cost and failure data, polyethylene networks show significantly lower costs throughout their lifetime, and the combined benefits of low failure and water loss rates can potentially result in long term cost savings.

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