Collaborative research on condition assessment and pipe failure prediction for critical water mains

Most major urban water utilities in Australia have extensive critical pressure main systems, parts of which have been in service for a century or more. As pipe breaks can have severe impacts on customers and safety, an international team of utilities, research organisations and technology providers initiated a global collaborative project developed to undertake research in partnership with local water utilities, local universities, international water bodies and pipe condition service providers. Dammika Vitanage, Jayantha Kodikara and Greg Allen discuss the project and its outcomes.

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It is generally recognised worldwide that about 70% of the total asset base of urban water utilities consists of buried pipes. Sydney Water has buried systems valued at over AUS$15 billion (US$13.6 billion), and this is typical of large utilities.

Most major urban water utilities in Australia have extensive large, critical pressure main systems, parts of which have been in service up to a century or more. Failure of critical mains has significant impacts in terms of maintaining service levels to customers, loss of fire fighting supply, safety, transport disruption and other social costs, as well as significant financial and reputational implications.

With further ageing of this vital infrastructure, supply main failures will continue to occur. This will have very high and growing cost implications for the sustainability and effectiveness of water and wastewater services. This is a worldwide issue, with potential impacts of climate change on soil properties and moisture, which lead to higher costs.

In Australia, the total replacement costs of pipe network have been estimated to exceed AUS$100 billion (US$93.1 billion) (Nicholas and Moore, 2009). Over the next five years, the costs of urgently needed asset replacement are around AUS$5 billion (US$4.7 billion). Maintenance costs over the same period are estimated at some AUS$2.5 billion (US$2.3 billion) (WSAA, 2009). Elsewhere, the USEPA estimates that the US public water sector will require $335 billion of capital investment over the next 20 years to sustain essential service levels. US studies also indicate that the average cost per failure for large diameter pipes exceeds $500,000 (Nicholas and Moore, 2009).

In response to these cost drivers, and to meet demands for reliable water supply services, water utilities have already made considerable efforts to control potential failures by applying existing, state-of-the-art methods for failure prediction, condition assessment and proactive pipe asset management technologies. The methods used have limited level of confidence, which limits the ability to target renewal programmes.

It has been conservatively estimated that even a 30% improvement in the present state of the art would reduce the high consequence events by 50% and total failure events by 30%, resulting in potential savings of over AUS$160 million (US$149 million) over a 20 year period to the Australian water industry. With better prediction from condition assessment, expenditure can be delayed by five years and replacement costs reduced up to 20%, so the projected savings over a 20 year period will exceed a further AUS$300 million (US$279.3 million).

Water utilities urgently need better techniques for estimating the probability of failure of critical pipelines and for estimating their remaining life. The unavailability of such tools increases the risk of substantial funds being potentially misdirected through premature replacements. This could impact on future water service pricing. On the other hand, not undertaking timely replacement of pipes could lead to an increasing number and frequency of failures, with associated costs and disruption.

In August 2011 an international project led by the Australian water industry with Monash University leading the research (www.criticalpipes.com) started pipe failure prediction, interpretation of advanced condition assessment using machine learning, and corrosion modelling.

The University of Technology Sydney and the University of Newcastle are the other two research partners. The Australian Utility partners are Melbourne Water, South East Water, Hunter Water, South Australia Water, and Water Corporation WA. Water Research Foundation (US), (WaterRF) and United Kingdom Water Industry Research (UKWIR) are the international research partners.

Scope of the collaboration

The international team developed a scope of research to improve the reliability of predicting large pipe failure. This included addressing the following research questions:

- How, when and where will pipes fail within the network?
- How do we assess the condition of the pipe cost-effectively?
- How do we estimate pipe deterioration rates accurately with respect to the pipe environment?
- What is the time-dependent probability of the pipe failure along the pipeline?
- How do we transfer the new knowledge to the industry for optimal pipe management?

Collaboration and its success

The current success of the research programme is due to the active collaboration and participation of the international team. Recently the project completed a technology transfer tour of the UK and US that was very well received by participating water utilities and the international

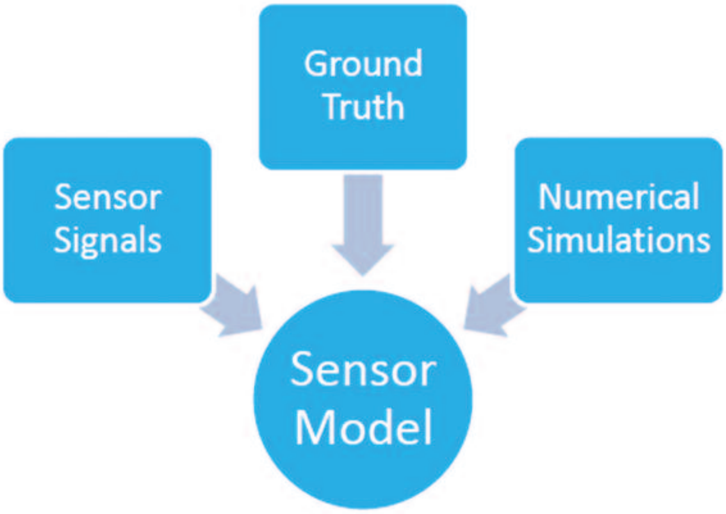


Figure 1
Governance structure of the advanced condition assessment and pipe failure prediction project

research organisations. The following demonstrates the collaborative success of the research project.

Industry partner initiation of and contribution to the project
The present research project was initiated by Australian water utilities. They sought the support of leading Australian and other researchers, and of key international partners. All were directly and actively involved in one local and one international workshop aimed at ensuring the viability and water industry relevance of the planned research. The active engagement of all parties proved that the research meets core industry needs and had considerable industry support. This was demonstrated by the industry partners' cash, in-kind and nominated expertise contributions, the access to critical water pipes, and engagement in case studies. Moreover, all partners have agreed to collaborate with each other for the benefit of the research, further demonstrating their commitment.

The involvement of collaborating partners
The industry partners involved in the project comprise the key major and some medium and small water utilities in Australia. They will contribute some AUS$4.15 million (US$3.9 million) in cash and around AUS$10 million (US$9.3 million) in kind. Their in-kind involvement covers much (>60%) of the non-labour in-kind support, to provide access to pipes and to cut out and replace pipes for research and investigation purposes. These activities have high enabling and contractor services costs. Further, the industry partners will contribute partner investigators, personnel time, sampling sites and participation in case studies. The three universities also provide significant cash and in-kind contributions to the research project.

There are five technology partners (or condition assessment service providers, as noted later) that will collaborate as partner organisations, with both cash and in-kind support. Acknowledging the uniqueness and importance of the project, WaterRF and UKWIR will provide AUS$1.2 million (US$1.1 million) in cash, and will provide substantial in-kind support to the project.

Relationship to the strategic plan of collaborating organisations
As noted earlier, in many cities large pressurised pipes are ageing and increasingly prone to failure. They are mostly located in built up areas, are under high pressure (50 to 80m head) and have very little or no redundancy. When these pipes fail, the consequences are 'catastrophic' – providing no services to customers and creating significant disruptions and safety hazards to the community. Evidently, reducing such failures is a major business and strategic priority for the utility partners. All have strategies for management of critical mains, but to date their success has been limited by the lack of knowledge and effective tools for optimal management of these assets.

Further collaboration and long-term alliances
An international planning workshop was held in Sydney (July 2009) for this project, and this was a critical catalyst in developing a proposal that met the core needs of all the partners. It established an international network that attracted the best expertise in the water industry and key university partners. Since the water and wastewater industry accounts for about 1% to 2% of GDP, international and industry-university cooperation and collaboration is essential.

To date the Australian industry partners have provided outstanding leadership in this area. Both this and international collaboration can be expected to continue and be enhanced as a result of the activities and research outcomes. A follow up planning session took place in October 2012 in Sydney that demonstrated the continuous engagement of the partners to review the progress and plan ahead to improve the research plan.

Partnership with technology providers to enhance condition assessment
Four technology providers have agreed through University of Technology Sydney to improve the data interpretation of their technologies with the project. Three research runs of two of their technologies have been completed with validation using the Sydney Water test bed site. One research run has been completed on one of the intrusive techniques and another is planned. The technology partners take part in the technical advisory committee special session every quarter, or as required. This direct engagement in improving the available technology is considered to be a successful collaboration, and is thought to be a world first in a large project of this nature.

Governance
A governance structure has been established to foster strong partnerships between industry partners and the research team, maintain rigorous probity in the expenditure or research funds, and disseminate research findings. Every three months the research project holds a management committee and technical advisory committee meetings to engage with water industry partners and international research organisations to ensure that the research is on track to deliver benefits to the water industry. Figure 1 is the outline of the governance structure.

Current results
The project was 20 months complete in June 2013, and substantial progress has been made in all three main activities. Pipe failure data has been collected to understand the status of the network performance of partners' critical pipes. These included past failure data, forensic or pipe failure inspection reports, condition assessment reports, and anecdotal evidence gathered through discussions with utility technical personnel.

Along with this, a major literature review has been completed in all three activities. The collected data and information were archived in a central server location so that all partners could access them. A report summarising the findings has been published

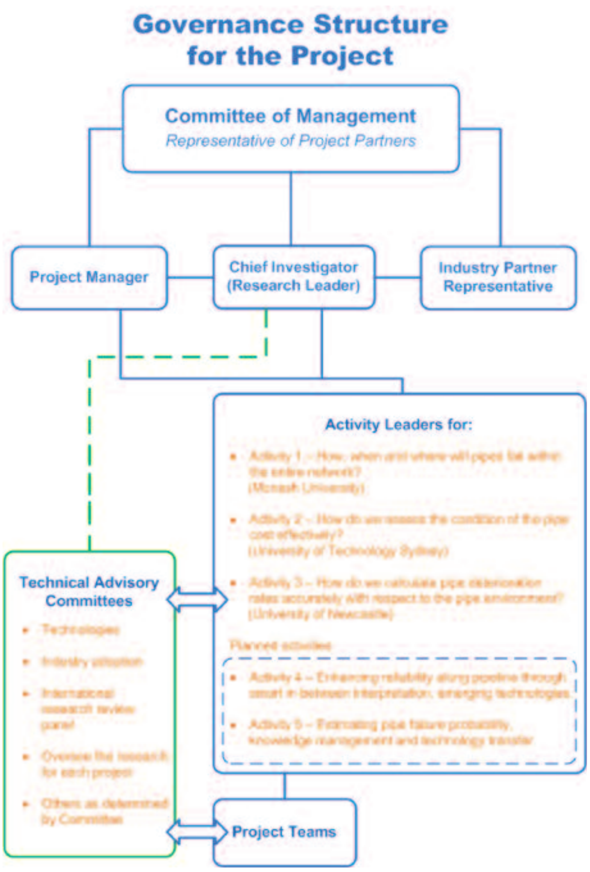
(Kodikara et al, 2012) and a companion paper is included in these conference proceedings (Rajeev et al, 2013).

One of the key field developments was the establishment of a dedicated test bed for pipe research. The test bed is a 1.5km-long decommissioned buried water pipeline laid in 1922 and located in Strathfield, NSW. It is a 600mm diameter, cement lined cast iron pipe with nominal wall thickness of 30mm and lead joints at approximately 3.6m intervals. The pipeline was made chargeable with potable water and was fitted with entry points for condition assessment tool insertion. A brief description of progress made in individual activity areas is provided below.

Failure prediction

The data analysis revealed that the majority of the critical pipe assets (>300mm) are cast iron and steel pipes, so the primary research focus is on these pipe cohorts. On the basis of the data and information collected, pipe corrosion was classified into three main classes for further analyses. These are: general corrosion, where corrosion is prevalent all around the pipe and could be idealised as a reduction in wall thickness; patch corrosion or graphitisation, where a patch of pipe is corroded; or pit corrosion, where a single pit or a cluster of pits have developed on the pipe wall. Analytical tools to compute pipe stress were developed for all three corrosion categories.

Figure 2
Approach for condition assessment sensor modelling



Of the external and internal factors that contribute to the pipe failure, traffic loads (a majority of the critical pipes are laid under roads), as well as water pressure and likely pressure surges were considered in more detail. In March 2013, a section of the test bed that crosses an arterial road to the Hume highway was fully instrumented to measure pipe response under live traffic conditions. It is expected that a useful data set, not only for pipe static analysis but also for analysis of pipe response to transient traffic loads, could be collected through this instrumentation.

Through the data analysis, the project identified that there is limited data on the pressure transients although they were considered to contribute to pipe failures. A pressure monitoring programme was initiated at selected partner networks, including the Hunter Water network. This was accompanied by hydraulic surge modelling to develop calibrated models that can be used to generate data across the network for pipe failure prediction. Another aspect of research is the development of a concept for 'smart' pipe monitoring, and the use of various sensor arrangements including distributed optical fibre sensors is being investigated (Rajeev et al, 2013).

Interpretation of condition assessment

Numerous sensor techniques such as ultrasonics, magnetic flux leakage (MFL), broadband electromagnetics (BEM), remote field eddy current technology (RFT) and acoustics are used in 'direct' pipe condition assessment. The main focus of the current research is developing new and improved automatic interpretation of sensor data using machine learning technology that is commonly used in robotics. The University of Technology Sydney (UTS) has developed collaboration with a number of external service providers (Rock Solid Group – BEM, Assed Integrity Australia with Advanced Engineering Solutions – MFL, Russel NDT Technologies / PICA – RFT SeaSnake, and Pure Technologies / Aqua Environmental – Sahara@PWA).

One of the key requirements of sensor interpretation is the availability of data and associated ground truth for data training or calibration. To date, a number of test runs have been undertaken in the test bed and ground truth was sourced by exhuming the pipe and undertaking measurements after grit blasting. A laser scanner has been used to collect ground truth data, which can produce a three-dimensional picture of the pipe surface to required accuracy. In addition, UTS has developed an automated ultrasonics (immersion probe) scanner for obtaining ground truth data. The overall process of sensor modelling is shown in Figure 2. More details of this research are presented in a companion paper at this conference (Valls Miro et al, 2013).

Prediction of corrosion

Corrosion is identified as the primary deterioration mechanism for cast iron and steel pipelines (Petersen and Melchers, 2012). To predict the remaining service life of buried critical pipes, a realistic predictive model of corrosion versus exposure time is required. Such a model should consider the main contributing factors in the buried pipe environment and be based on mechanistic approaches to be more generally applicable.

Petersen and Melchers (2012) have highlighted that such a model does not exist, although several quasi-empirical and empirical models have been proposed. In particular, they highlighted that current models use either power law or exponential curves to fit data, whereas it is more likely that a bi-model trend would better represent the corrosion process in buried pipes. The approach adopted is to develop field calibrated models that are based on fundamental corrosion science and physics.

Identifying that the past data on corrosion measurements are not fully amenable to mechanistic corrosion model development, a new protocol for data collection has been developed. The protocol involves a detailed procedure to be followed after exhuming a pipe for inspection. It involves collecting soil samples, pipe and burial details with photographic records, and scanning pipes using a 3D laser scanner before and after grit blasting. Currently, this protocol is being used in the Hunter Water network and more details are available (Petersen et al, 2013; Dafter and Petersen, 2013).

Uptake by the water industry

There are a number of strategies in place to facilitate technology transfer and uptake by the water industry to achieve early benefits of the research. They have all been designed to achieve active engagement through 'champions' and user groups from industry partners. The technical advisory committees sit every three months and comprise the industry partners from Australian Utilities, WaterRF and UKWIR. Industry partners are also engaged through planned and historical review of case studies to validate the research outcomes.

The 600mm cast iron test bed is a significant outcome of the project, for conducting research within a pipe environment. The world's first research test bed where the interpretation of the condition, failure and corrosion of the pipe is being actively researched has provided a significant opportunity for Sydney Water and other industry partners to provide more insights into pipe failure. In addition to its current use, it is expected that the current test bed could be a global facility that can be used to test pipe related research in future, including pipe rehabilitation technologies.

Case studies on pressure transients in Hunter Water and the collation of the environmental information around the pipe for calibrating the corrosion model has resulted in sampling protocols for mains break data collation and planning renewal programmes. Hunter Water, Sydney Water and Water Corporation WA have incorporated the sampling protocols into their normal business processes.

With new knowledge on failure prediction, utilities have the ability to review conservative decisions on renewal planning and have the opportunity now to better understand the risks to take more realistic decisions.

With the demonstration of the improved data interpretation ability on condition assessment the industry partners have the ability to better understand the need to define the uncertainty based on a scientific approach. This has enabled new thinking in defining specifications for condition assessment technology providers. Already these benefits provide considerable potential to save 10% of the renewal costs of critical mains, with improved targeting of the high risk mains.

Expected benefits to the collaborating organisations

The Australian industry partners participate in various research components, including pipe monitoring, pipe deterioration, condition assessment, pipe failure analyses, database management, economic analysis, validation and targeted case studies. The benefits of this participation flow directly to the industry partners, providing an improved skills base that will allow more effective future pipe asset management. This could also bring them significant financial benefits.

Benefits of the research to the wider Australian water industry

The benefits to the wider Australian water industry and also to the international water industry include: more rational methods to determine how, when and where pipes are likely to fail in the network; prioritisation of factors that affect pipe failure, with guidance on what to look for in condition assessment and on possible methods to reduce pipe failures; innovation in cost-effective condition assessment techniques and guidance to choose them; improved knowledge guidance, decision support and education workshops for optimal pipe management; and tools, methods and strategies with a defined level of low uncertainty, and an increased level of confidence in predicting the probability of failure, to target critical main replacement.

Expected economic and social returns to the broader Australian community

As noted, the project outcomes will contribute to the continuation of reliable, undisrupted and safe water supply to Australian communities. It will reduce social, economic and environmental impacts associated with critical pipes failure. There also will be substantial cost savings. As highlighted earlier, as a conservative estimate, a 30% improvement in present state-of-the-art can deliver AUS$160 million ($US149 million) over 20 years and if this result in delay of current expenditure in pipe replacement for five years, a further AUS$300 million (US$280 million) can be saved over this period (Nicholas & Moore, 2009). In turn, these cost savings will help sustain lower water prices, benefiting the community at large. This does not include the very significant intangible benefits to the community of avoiding major disruptive events that lead to losses of homes, closures of roads, parklands, shops, and so on, and, of course, loss of water. Internationally, even larger benefits apply.

Concluding remarks

This article has summarised some details of a global collaborative project developed to address the management of critical water mains. The strength of the project is achieved through partnership between local water utilities, global water bodies, condition assessment service providers and local universities as research providers.

In contrast to pure academic activity, the research is focused through real industry needs and active industry participation. Nonetheless, bottom-up scientific research is being pursued, seeking to fill knowledge gaps and produce solutions that present a significant advance from the current state-of-play, yet can be directly used by the utilities. The approach adopted by the collaborators is geared to produce benefits for all parties involved, representing win-win conditions. ●

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References

Dafter, M and Petersen, R (2013), Advanced condition assessment of Hunter Water's cast iron watermain. Corrosion and Materials, Australian Corrosion Association, Vol 38, No 3, pp42-45.

Kodikara, J, Rajeev, P, Robert, D and Zeman P (2012), Critical review of historical information on large diameter pipe failure. Report of Monash University, Monash University, Melbourne.

Nicholas, D and Moore G (2009), Condition assessment and failure prediction of pressure pipelines: scoping study for ARC Proposal. Report prepared for Water Services Association of Australia. Water Services Association of Australia, Melbourne.

Petersen, RB, Dafter, M and Melchers, RE (2013), Long-term corrosion of buried cast iron water mains: Field data collection and model calibration. LESAM 2013, 10-12 September, Sydney.

Petersen, RB and Melchers, RE (2012), Long-term corrosion of cast iron cement-lined pipes, Corrosion and Prevention 2012, Australian Corrosion Association, 11-14 November, CDRom Proceedings, Melbourne.

Rajeev, P, Kodikara, J, Robert, D, Zeman, P and Rajani, B (2013), Factors contributing to large diameter water pipe failures as evident from failure inspection. LESAM 2013, September 10-12, Sydney.

Rajeev, P, Kodikara, J, Chiu, WK and Kuen, T (2013), Distributed optical fibre sensors and their applications in pipeline monitoring. Key Engineering Materials, Vol 558, pp424-434.

Valls Miro, J, Rajalingam, J, Vidal-Calleja, T, de Bruijn, F, Wood, R, Vitanage, D, Ulapane, N, Wijerathna, B and Su, D (2013), A live test-bed for the advancement of condition assessment and failure prediction research on critical pipes. LESAM 2013, 10-12 September, Sydney.

WSAA (2009) National Performance Report 2007/2008. Report of Water Services Association of Australia. Water Services Association of Australia, Melbourne.

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