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IMPLEMENTING RESEARCH INTO THE MANAGEMENT OF CRITICAL WATER MAINS

Renewal of large diameter water pipes based on failure prediction

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ABSTRACT

Many major urban water utilities in Australia have a significant number of critical water mains that have been installed a long time ago and are in a state of reaching the end of their designed service life. Pipe failures are inevitable across all utilities and when they occur they can cause severe consequences for the public and the surrounding environment. This has been a serious challenge to water utilities mainly due to the limited knowledge available in accurately predicting the critical water main failures. To overcome these challenges, a global collaborative research project was conducted (Advanced Condition Assessment and Pipe Failure Prediction-(ACAPFP) project) in Australia from 2011-2016 led by Sydney Water (SW) with the participation of a number of local water utilities, two international water bodies and three research institutes. The project has advanced the fundamental engineering science in pipeline failure definition and innovated several tools to predict critical water pipe failures. Significant outcomes from this research project need to be integrated into SW's business practice with validation across a larger cohort of pipes to benefit customers and shareholders. This new three-year 'operationalisation' phase is aiming to achieve a further 4% efficiency in critical water main renewal programs with a higher level of customer service.

INTRODUCTION

A large-proportion of critical water mains own by many Australian water utilities consist of large-diameter cast iron pipes, some of which have been in service for a century or more. The pipes have been sitting on various aggressive environments where they are subjected to gradual but continuous deterioration. In addition, rapid urbanization adds demanding operating conditions on critical water mains causing high stresses on them. These factors lead pipes to fail. Pipe failures causes significant impacts in terms of maintaining service levels to customers, loss of water supply, safety issues, transport disruption and other social costs, as well as significant financial and reputational implications. Moreover, quantification of the current state and performance of critical water mains is essential for the water industry as utilities are under tremendous pressure to do more with less.

To address these challenges, a global collaborative research project, the Advanced Condition Assessment and Pipe Failure Prediction (ACAPFP) project was undertaken. The research project was led by Monash University with University of Newcastle (UoN) and University of Technology Sydney (UTS) being the other two research partners. The Australian water utility partners of the project were Sydney Water Corporation (SW) (lead), Water Corporation (WA), City West Water, Melbourne Water, South Australia Water Corporation, South East Water Ltd, Hunter Water Corporation, Queensland Urban Utilities, and Yarra Valley Water.

The international partners of the project were the UK Water Industry Research Ltd. and the Water Research Foundation of the USA. The project was funded in cash ($5.9 million) and in-kind funding of $16.5M million. The project ended in early 2017 with significant advancement of knowledge on the performance of large-diameter water pipelines. The project received a number of high impact awards, including the prestigious International Water Association 2016 Project Innovation Award in the Applied Research category for the contribution made to the global water industry.

In 2017, Sydney Water provided $4 million in funding for the operationalise phase of the ACAPFP project. The aim is to implement the findings of the ACAPFP project into the Sydney Water pipe network. The research partners of the second phase of the research project (operationalise phase) were Monash University, UoN, UTS and Data61-CSIRO.

THE KEY RESEARCH OUTCOMES OF THE ACAPFP PROJECT

The ACAPFP Project investigated a number of aspects related to the performance of large-diameter cast iron pipes. The overall goal of the project was to make definite advancement in critical water pipeline condition assessment (CA) and failure prediction. The project had four main activities that were carried out across the three research institutions involved, with close supervision of the project by industry partner. The significant findings of each of these activities are summarised below.

Activity 1: How, when and where will pipes fail within the network?

The failures in large-diameter pipes can be broadly categorised into two main categories: failures in the pipe barrel and failures in the pipe joint. In this activity, the scope of the research was limited to pipe barrel failures. Based on the number of failed pipe observations, it appeared that the main failure mode associated with pipe barrels was longitudinal fracture. The scope of this activity included investigation of the effect of internal and external factors on pipe performance, measuring pipe material properties, understanding pipe failure mechanisms and developing stress prediction tool incorporating all relevant factors.

Past pipe failure data collected from five partner utilities including Sydney Water were analysed. Longitudinal fracture was identified as the most frequent failure mode and the main cause of many many longitudinal pipe failures were corrosion and pressure transients. The analysis also found that a significant number of failures occurred at the road verge. Field pressure monitoring and numerical modelling of pressure transients indicated most of the generated pressure transients dissipate rapidly (within a 2-3 km distance) depending on the pipe network configuration and the time of the day (i.e. pressure transient generated at night had poorer dissipation than during the day). Network locations that are susceptible to high pressure fluctuations during an event of pressure transient have been identified (Rathnayaka et al 2016a). In addition, a GIS based technique was introduced to incorporate validated results of numerical modelling of pressure transients to pipe asset database for failure prediction (Rathnayaka et al 2016b).

A dedicated pipe test bed provided by Sydney Water was utilized by the research team to measure pipe performance under a range of traffic conditions. It was found that changes in pipe strains from trucks passing and braking were similar. The measured pipe strains under extreme traffic scenarios were within the elastic region of pipe material and strains were 5-6 times lower than the strain induced by typical operational water pressure (500-600kPa). Extensive laboratory testing (pipe burst testing) was conducted to identify the pipe failure mechanisms in large-diameter cast iron pipes. Based on pipe burst test observations, a failure initiation at typical operating water pressure required a large corrosion patch and significant reduction of wall thickness (>80%). If these conditions are not met, the failure pressure was excessive (e.g. 125mm diameter corrosion patch with 72% wall thickness reduction failed above 3MPa pressure). Condition assessment for large-diameter pipes should focus on identifying large and deep corrosion patches rather than smaller pits. Large diameter cast iron pipes start to leak water once failure is initiated (a crack). Such cracks grew under repetitive loading such as pressure transients and further corrosion. Based on these findings, it is proposed that there is a window of time between crack initiation and a burst and leak-before-break concept can be use as prediction tool to prevent pipe failures and proactive asset management (Rathnayaka et al 2017). Leaks may be monitored to detect pipes that are close to failure, thereby possibly preventing future failures.

The pipe stress prediction tool (applicable for longitudinal failures) is a Microsoft Excel based spread sheet that was developed using the results of a large number of validated finite element modelling, simulating range of pipe sizes and loading conditions in the ACAPFP project. It has the capability of calculating the maximum stress induced by the corrosion patch in pipe barrel sections, incorporating internal water pressure, traffic load, soil load and rate and degree of corrosion. A methodology to analyse a cluster of pits or patches has also been developed. The condition assessment data – geometry of corrosion patches (Activity 2) and rate of corrosion (Activity 3) was fed into the tool to conduct the analysis. The tool is also capable of incorporating uncertainties in input parameters to calculate the probability of pipe failure (Ji et al 2016, Robert et al 2016).

Activity 2: How do we assess the condition of the pipe cost effectively?

This activity investigated the strengths and weaknesses of commonly used pipe condition assessment technologies by water utilities to assess the condition of cast iron water mains and their ability to provide information specified by Activity 1 for pipe failure predictions. It was found that some techniques were better suited at representing point measurement of wall thickness, while others represent measures of average volume of material under the sensor antenna. The resolution and accuracy at which pipe wall defects can be reported were better understood. As identified in Activity 1, most of the barrel failures in large-diameter cast iron pipes are associated with large patches with significant depths. Commercial providers of CA tools for large cast iron pipes do not currently provide information in their reports that can produce thickness maps suitable to conduct failure analysis proposed by Activity 1 (i.e. information about area of corrosion patches is not provided).

Algorithms and methods were developed to make the generation of thickness maps possible to characterise large patches from the data acquired from CA tools. Interpretation strategies and software packages were produced and shared with the respective CA technology providers engaged in the project. It is understood that validating CA interpretations is a difficult process for utilities. A current outcome from this activity offered utilities a proven metrology solution based on 3D laser scanning inspection of reference pipes to attest the suitability of local and direct CA tool advances to be readily incorporated into the failure prediction framework (Skinner et al 2014).

Pressure Wave propagation-based techniques have shown to lack the necessary sensitivity to be able to detect pipe wall losses/defects in large metallic pipes as required by failure modelling needs.

The age, manufacturer method, soil moisture level and backfill quality were identified as key parameters that effects uncertainty in the use of non-destructive, indirect measurement with LPR.

Activity 3: How do we calculate pipe deterioration rates accurately with respect to the pipe environment?

With lack of data and difficulties associated with interpretations, it was assumed that the process of corrosion in buried cast iron pipes would be similar to that occurring in other ferrous metals in other natural environments, such as fresh water, immersion in seawater, and in the tidal and atmospheric zones. A specific non-linear bi-modal corrosion progression model was utilised to model the corrosion propagation of buried cast iron pipes (Petersen et al 2013). The Activity 3 research team characterised corrosion in cast iron using two parameters, r_s (long term corrosion rate) and C_s (intercept signifying the corrosion level reached in the initial level), giving the corrosion pit depth as a function of time as ($Cs + r_s t$) where t is the time. This model has been extensively calibrated and validated using existing and new data collected throughout the ACAPFP project (Petersen et al 2013).

It was found that corrosion only occurs to a significant extent when there is enough moisture and oxygen (oxygen found to be less important in the long-term) next to the corroding surface, and this is regulated by the soil and also by the graphitised layer between the soil and the corroding surface (for cast iron). When there is sufficient moisture at the corroding interface, the corroding conditions were similar to those under immersion conditions. Corrosion in soils occurs under essentially stagnant conditions and is therefore independent of soil water chemistry. Once a pipe wall is perforated by a corrosion pit, the interior high-pressure freshwater will escape into the interface between the cast iron and the graphitized layer and there cause general corrosion leading to areas of pipe wall thinning. Soils with some nitrate content showed higher level of corrosion, attributed to microbiological influenced corrosion.

Activity 4: How do we assess the time-dependent probability of failure along the pipe?

A new framework has been proposed to conduct along the pipe CA. From a small number of local inspections, the "along the pipe" framework could produce likely thickness maps present in the pipeline, which includes the likelihood of the most relevant extreme condition for CA and failure prediction (minimum thicknesses, patch geometries). This information was fed into the pipe stress prediction tool developed in Activity 1 for failure predictions. It was found that probability of failure is greatly affected by the wall thickness, water pressure and corrosion rate. Physical modelling results showed that the probability of failure follows a Weibull distribution.

HOW THE OUTCOMES HAVE ACHIEVED EARLY BENEFITS?

Direct benefits of the project have resulted in deferring $10M worth of renewal investment with the improved understanding of the likelihood of failure of these critical water mains, coupled with other improved asset management strategies. The ACAPFP, a six-year international collaborative research has improved the prediction of pipe failures. This has been achieved by improving the knowhow of the mechanisms of failure of metallic pipes, interpretation of condition assessment information and parameters governing pipe failure and corrosion mechanisms. To date, learnings from the ACAPFP project have allowed us to improve our understanding of future pipe condition information by amending condition assessment contracts and data collection protocols. It has also contributed to an annual reduction with Sydney Water's Critical Water Main (CWM) renewal program from $40M in 2008–2012 to $30M in 2012–2016 (Zhang, et al, 2016).

WHY IT'S ESSENTIAL TO OPERATIONALISE AND THEN IMPLEMENT THE OUTCOMES?

Substantial investment and effort was made by all participating water utilities, research institutions and technology providers towards successful completion of the ACAPFP project. Although a number of initial benefits were made by a number of water utilities involved in this project, the true and complete benefits of the significant body of knowledge developed in the ACAPFP project can be obtained only through systematic implementation of research outcomes into the routine practice of the water utility business. Such a systematic approach will allow to further validate research findings and identify practical difficulties associated with the proposed research outcomes.

Further, operationalising research into practical application would assist to enhance the communication between research teams and practicing engineers to allow efficient knowledge transfer for practical use.

ACAPFP OPERATIONALISE PHASE

Objectives and expected outcomes

The objectives of this operationalise phase are to further validate and refine the research findings in the ACAPFP project, consolidate research outcomes into practical tools through applying the learnings; and to embed the tools in business-as-usual practices.

Outcomes planned with completion of the operationalise phase are:

- Reduce CWM renewal program by 4% (~$5 million) between 2016–2020;
- Provide a set of tools to prioritise and develop a robust and defensible CWM renewal program for 2020–2024, by identifying the right sections of mains for renewal
- Improve asset performance, customer satisfaction and confidence in investment decision makings of the Sydney Water pipe network
- Provide a process platform for continuing improvement through advancing knowledge of pipe failure.
- Interpolation between points of condition assessed is only statistical at present. An attempt will be made to improve this during operationalisation phase.
- A preliminary model will be included in to the pipe stress prediction tool to quantify the impact of pressure transients on asset performance.

Methodology

The operationalisation project is planned to be carried out in three phases:

Phase 1: Validate the learnings

The ACAPFP project advanced the knowledge on performance of large-diameter cast iron pipes in many ways. One of the major challenges faced during the failure prediction of large diameter water pipes was lack of failure records. Therefore, use of statistical based (data driven) failure prediction methods did not produce accurate predictions for large-diameter pipes. This led the ACAPFP project to focus on developing a physical failure prediction model (MS Excel based) incorporating all physical parameters affecting pipe performance including internal and external loading, rate and degree of corrosion, pipe properties and associated uncertainties in input parameters. The model is extensively validated using laboratory experiments and field case studies. In addition, the project advanced knowledge in the areas related to pipe performance such as of traffic and soil loads, pressure transients, corrosion propagation and improving condition assessment interpretation.

In the operationalization phase, these finding will be incorporated in Sydney Water's operations by applying research outcomes in selected pipelines and assessing their performance.

Phase 2: Develop, calibrate and integrate the software tools

Although the ACAPFP project has developed new tools for failure prediction, most of them have only been verified using limited field applications. The tools need further validation and calibration by testing against a different cohort of pipes in multiple locations so that Sydney Water has confidence in the tools and their condition assessment techniques. Therefore, in the operationalisation phase, several tools are to be developed and verified. These include: (a) a tool for prioritisation of pipes based on likelihood of failure using data analytics; (b) a corrosion prediction and propagation tool; (c) a tool for pipe failure analysis considering external and internal factors; (d) a tool for the probability of pipe failure 'along the pipe', incorporating statistical interpretation of information in-between measurements.

Phase 3: Implement and integrate the tools into the business

Implement the new tools through a change of management process to build in-house skills and capability and better capture and use of project information.

Figure 1 shows how the different components of research (Data61, findings of the ACAPFP project and operationalise phase) will be brought together to improve pipe failure prediction so that the risk can be more accurately assessed.

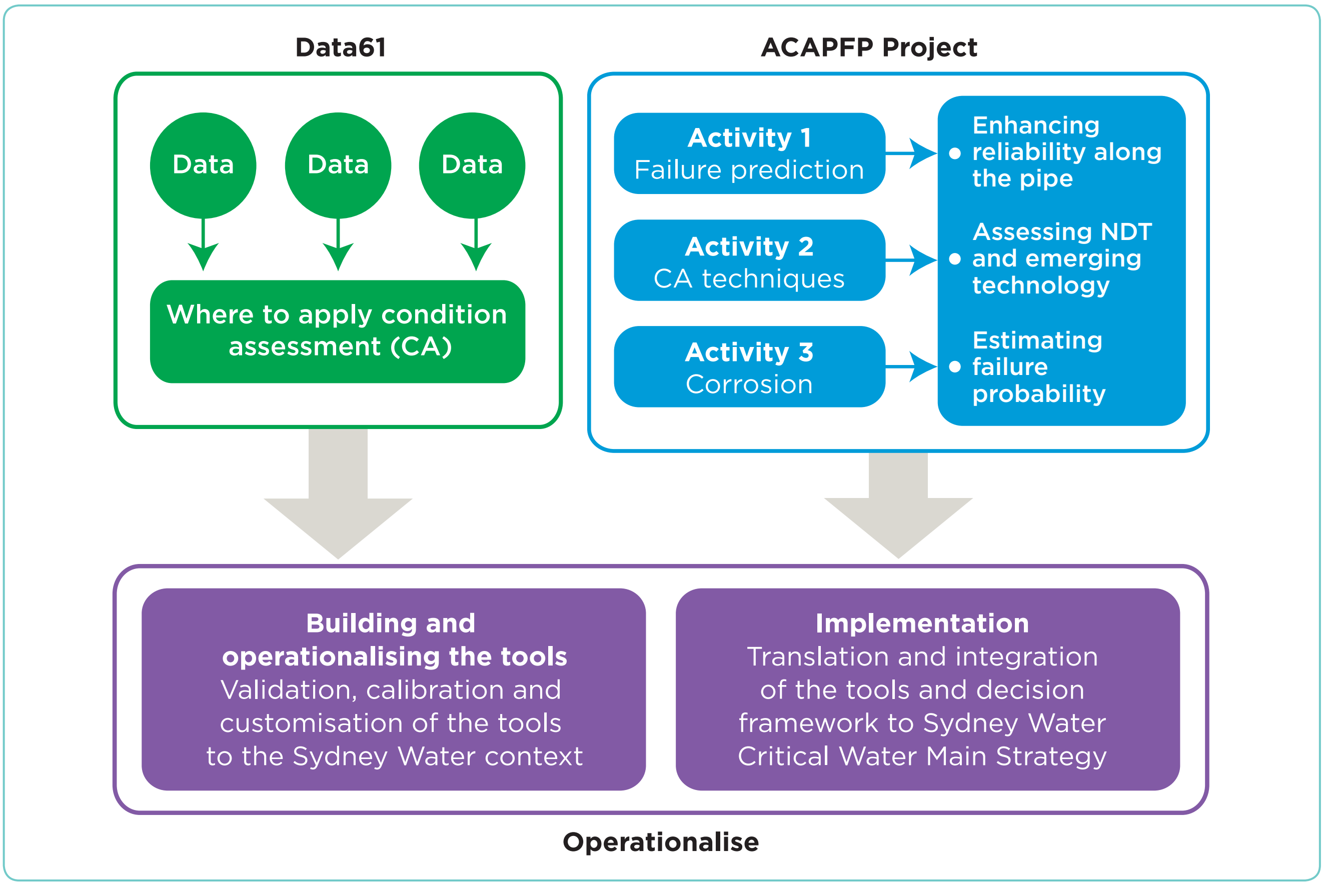

Figure 1: Operationalisation of ACAPFP

The methodology will include selecting a list of priority pipes based on the Data61 statistical failure prediction model (Li et al. 2014). The other research teams involved in the operationalise phase of the project will develop a physical modelling approach to confirm and prioritise the pipe sections selected by Data61 to include in the Sydney Water future asset renewal program. The analysis will have two levels (Level 1 and Level 2), which involve collecting all physical parameters necessary to assess pipe performance, including pressure transient, traffic load, and corrosion data that can be utilised in failure prediction using the pipe stress prediction tool developed in the ACAPFP project (Kodikara et al. 2017).

The outcome of the failure predictions obtained using the above tool will be further checked and confirmed. Sydney Water will employ their CA contractors to assess pipe condition and obtain raw data on selected pipes. UTS will recommend CA tools to conduct CA and UoN will conduct analysis of soil sampling along the pipeline. Based on this information, Monash will re-run the pipe failure prediction tool to refine high / low risk areas along the selected pipe segments to finalize the priority list. This information will be fed back into prediction models to re-calibrate model accuracy.

A user driven project management team has been set up with the relevant team members of Sydney Water. The same team members will work with researchers directly through the technical advisory committee sessions of the research and innovation phase. The strategic leadership team will review the progress of the implementation phase based on the inputs from the user group.

CONCLUSIONS

A significant advancement of knowledge was made in the ACAPFP project related to large-diameter cast iron water pipe performance which are commonly used by many water utilities around the world. To achieve the full benefits of this research we now need to fully 'operationalise' the learnings from the ACAPFP project, along with a separate data analytics project run by Data61 to create and implement analysis tools to support the Sydney Water asset management strategy. These tools will allow us to identify and justify mains for condition assessment and renewal with greater confidence to achieve cost and service efficiency.

The ACAPFP project has improved our understanding of pipe failure theory, accuracy of current condition assessment techniques and cast iron pipe corrosion processes. The Data61 research applies machine learning to identify pipes with the highest likelihood of failure using pipe performance, asset attribute and environment data. Success in the operationalise phase will place Sydney Water at the cutting edge of world's best practice in pipeline condition assessment.

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