6th International Conference on Structural Engineering and Construction Management 2015, Kandy, Sri Lanka, 11th-13th December 2015

SECM/15/154

Development of an integrated software tool for whole of life management of concrete storm water pipe assets.

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Abstract: In Australia, there are 500 local councils, each managing 300-1000 km of storm water drainage systems. Majority of the storm water pipes are concrete and are built in 1960's. Currently the councils use CCTV inspections to assess around 10% of the network and make maintenance decisions for the whole asset stock. This creates a major challenge for asset managers since the decisions are made based on assumed levels of deterioration. Catastrophic failure of pipes due to inefficient management will lead to flooding, which can be a major hazard to the community and infrastructure. The paper presents the outcomes of a study conducted to assess the whole of life performance of concrete storm water pipes. Data from CCTV inspections are converted to a discrete rating and are used to derive Markov chain based deterioration models for the network. Based on these, optimized inspection strategy is developed for the pipe assets combined with a life cycle costing module, tree root invasion model and hydraulic and structural failure modules. The proposed integrated management model is suitable for capturing the whole of life performance of any infrastructure asset.

1. Introduction

Storm water pipelines are essential infrastructure that plays a pivotal role in Australia's economy, prosperity, social well-being, quality of life and the health of its population. If the catastrophic failures of these pipes can be prevented, the economic, environmental and social significance of this prevention is far-reaching and cannot be assessed by a single measure. In Australia, there is approximately 300,000 km of concrete pipes with an estimated total asset value of $45 billion (Concrete Pipe Association of Australasia). Most stakeholders of pipe infrastructure have recognized the severe consequences of pipe failures. As such there is on-going research funded by industry, e.g., the Water Service Association of Australia and the Water Research Foundation (US).

The life expectancy of buried concrete storm water pipes can exceed 100 years, but the age of failed pipes, e.g., cracked or collapsed, is much shorter. In Australia, the 2010 infrastructure report card for Victoria (Engineer Australia, 2010) rated storm water pipes at C-, meaning that major changes are required to be fit for the current and future purposes. Most recent collapses of concrete pipes that can be classified as catastrophic to the public are related to pipe deterioration: (i) the collapse of the Cunningham Pier main drain in Geelong in 2014 resulting in discomfort of road users; (ii) the collapse of a trunk drain in Southern England causing disruption and diversions near the railway station in 2010; and (iii) the collapse of storm drain in South Carolina in 2014 causing a day-long road closure.

Various attempts have been made to develop a practically useable technique for failure prediction of buried pipes. Moore et al.(2004) investigated the soil–pipe interaction of buried concrete pipes. Busba and Sagues (2013) conducted experiments to study the effect of cracked surfaces on the corrosion behaviour of reinforcing steel in concrete pipes. Mahmoodian and Alani (2013) studied the reliability of concrete pipes subjected to thickness reduction due to sulphide attack. In Australia, limited research into buried concrete pipes has been carried out. Sharma et al (Sharma et al., 2008) developed a dynamic model to predict sulphide production in a concrete storm water system. Tran et al (2010) applied Markov theory to model the deterioration of storm water pipes by using CCTV data.

The reoccurrence of unexpected pipe failures has demanded a better and implementable asset management framework for buried drainage pipes. This study proposes an effective asset management framework (AMF) and describes a software tool developed to implement the AMF for storm water pipes.

2. Asset management framework

The asset management framework (AMF) of drainage pipe assets is developed in this study based on:

- The general view of asset management policy set out by asset owners and operators (i.e. Local Councils)

- The requirement of Australian Accounting Standard (ASSB 116), which states that the useful life of asset be reviewed at least at the end of each annual reporting period so that adequate depreciation is applied.

- The suggested management method described in the Practice Note 5 issued by Institute of Public Works Engineering Australasia (IPWEA) for storm water drainage pipes (IPWEA, 2015).

The AMF consists of 6-step as described in the following:

1. Assign criticality rating (or failure consequence) to each drainage pipe asset
2. Collect condition data of pipe asset
3. Estimate time-based failure probability
4. Conduct risk analysis
5. Monitor and control risk
6. Conduct annual review

Assigning criticality rating

With a large network of buried drainage pipes, it is not affordable to inspect and perform repair on all pipe assets at the same time. Therefore, it is recommended that the criticality rating is assigned to each pipe asset based on some criteria such as social-economic consequences (if the asset fails unexpectedly) for prioritized maintenance program. The social consequence is discomfort of community, traffic disruption and bad reputation and so on, which can be quantified by some penalty value. The economic consequence is the business loss, accident compensation and litigation cost.

Collecting condition data

The CCTV inspection method can be used to collect condition data in terms of structural condition (e.g. 1-5 condition grading) and structural defects (e.g. cracks and corrosion of reinforcing steel), which focuses on structural failure or pipe collapse. On the other hand, hydraulic (or serviceability) condition (e.g. 1-5 condition grading), and hydraulic defects (tree roots and deposits) are dependent on pipe overflow and flooding.

A condition grading scheme can be applied to pipe defects to produce a qualitative assessment of overall structural and hydraulic condition (called snapshot condition) at the current time. The snapshot condition appears to be suitable for drainage pipe assets because CCTV data shows that pipes often have different defects caused by various mechanisms including random attack. Currently, available Australian grading schemes are the IPWEA Practice Note 5-2007 and Water Services Association of Australia (WSAA)'s Inspection Code 2013 (WSAA, 2013).

For analysis of condition data, Tran (2015) recommended to collect at least 600 data points of condition data from a random sampling strategy, which can be applied to the cohort of critical pipes (at least) or the whole network (at best). For each data point, at least the construction year and inspection years must be known. It is well known that reliability of data will enhance the predictions.

Estimating failure probability

A failure must be defined. For example of a structural failure, it can be defined as load on pipes exceed the pipe strength at crack (called proof strength) or pipe strength at collapse (called ultimate strength) as per Australia Standard (AS 3725, 2007). For example of a hydraulic failure, it can be defined as peak flow load exceed pipe's flow capacity.

When information is not sufficient to conclude a failure, the probabilistic approach is recommended to estimate the likelihood of failure (or failure probability) over time.

Conducting risk analysis

Risk is generally quantified as the product of quantitative consequence and the failure probability, which are described in Step 1 and 3. Risk analysis is conducted to provide risk ranking of assets, which can be used for prioritized repair and replacement programs on high risk assets. The risk analysis also helps to identify environmental factors (e.g. inspection information, corrosion of steel, concrete cracking tree root) that most affect risk.

Monitoring and Controlling risk

Risk can be monitored through regular inspection program and can be controlled by taking maintenance actions and adopting best management practices in design, installation and operation.

For the regular inspection program, it is essential to determine optimal inspection frequency and adequate inspection method that can minimizes cost and maximizes benefit. Some experience-based recommendations are available as described in IPWEA's Practice Note 5. A better alternative is based on predictive modeling.

For risk control, it is imperative to determine when, where and how maintenance actions should be carried out to minimize risk and cost. This can be achieved through combining experience and predictive modeling.

Conducting annual review

The annual review is conducted to provide:

- Report of current status and performance of assets
- Update of remaining life of assets
- Annual budget for inspection and maintenance program.

OVERVIEW OF SIMS

The Stormwater-Pipe Inspection Management System (SIMS) is a software tool, which is run on web based platform hosted in cloud. http://www.assethub.com.au/sims_v1/Home.aspx

SIMS is developed by RMIT University in collaboration with Melbourne Water and 6 City Councils (Brimbank City, City of Darebin, City of Greater Dandenong, City of Monash, City of Port Phillip and City of Whittlesea) through a research project "Whole Life Care for Asset Management of Stormwater Drainage Pipe Assets" from 2013-2015.

SIMS is aimed to help managing stormwater pipe assets to achieve the following objectives:

1. Implementing of a comprehensive risk-cost effective asset management program for stormwater drainage pipe assets;

2. Focusing on structural safety and hydraulic serviceability

3. Complying with IPWEA guidelines (Practice Note 5, 2007), asset accounting Policy of Accounting Standards for Statutory Boards (ASSB) and best practice recommendations by the industry.

The current version (2015) of SIMS is applicable to concrete pipes only. One effective feature of SIMS is that a notification email of task completion will be sent to user if it takes long time to process a user-command. SIMS presents results in figures, tables and text files.

3. Demonstration

SIMS implements steps 3 to 6 of AMF. The following steps are explained to use SIMS.

- Import data
- Run Markov deterioration model
- Run Markov inspection model
- Run Markov lifecycle model
- Run Markov reliability model
- View results

Import pipe data

Import pipe data module is aimed to store information on individual pipe assets and related factors (e.g. ID number, construction year, pipe diameter, pipe inspection, pipe maintenance and so on) for analysis and modeling. Figure 1 shows the menu for import of pipe data and pipe inspection. A template can be downloaded for filling data and then uploading.

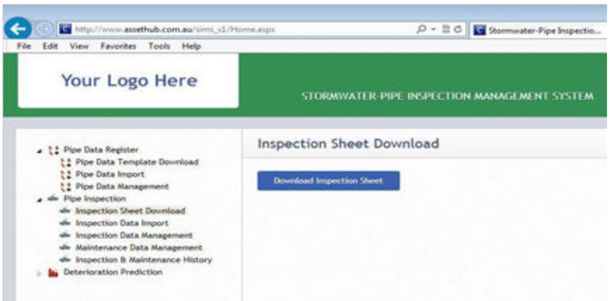

Figure 1 Importing data into SIMS

Run 'Markov Model Analysis'

Utilizing the CCTV condition data, a Markov deterioration model is derived based on the Markov chain theory, which predict the probability of condition change over a unit time. For example, with a typical 5-condition status as described above, if a pipe is in current condition 1, there will be 5 predictive transition probabilities that the pipe will stay in the same condition or move to another 4 possible condition next year. The calculation of predictive transition probabilities is shown in Equation 1 (Tran et al., 2010):

$$[p_1^t \; p_2^t \; p_3^t \; p_4^t \; p_5^t\,] = [1\;0\;0\;0\;0] * \begin{bmatrix} P11 & \cdots & P15 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & P55 \end{bmatrix}^t$$

Where p_1^t is predictive probability in condition 1 at time t, [1 0 0 0 0] represents for current condition, p12 is transition probability from condition 1 to condition 2,

The model is used to provide condition change over time for the whole network or pipe cohorts, which can be used for preparation of annual budget and asset valuation of the whole network over time. The model can also be used for an individual pipe that is considered to belong to the relevant pipe cohort or pipe network. Detailed description and calibration of the Markov model are described in (Tran et al., 2008, Tran et al., 2010).

Figure 2s shows that a user can apply the Markov model for structural or hydraulic condition. Figure 2b shows that pipe cohort can be selected for analysis by applying filtering on related factors. Figure 2c shows various options for running Markov model.

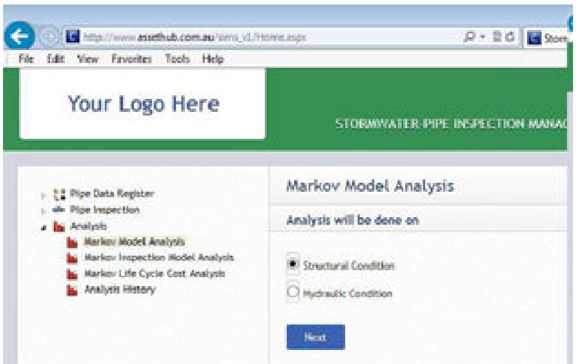

Figure 2a Running Markov model

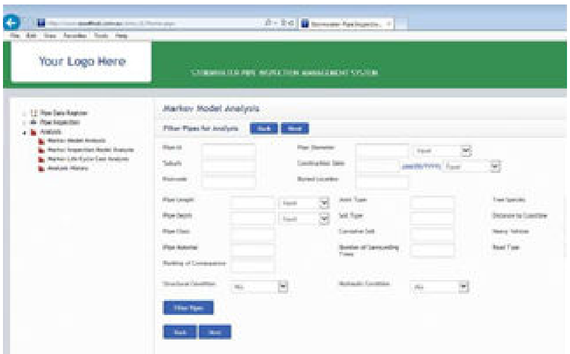

Figure 2b Pipe filtering

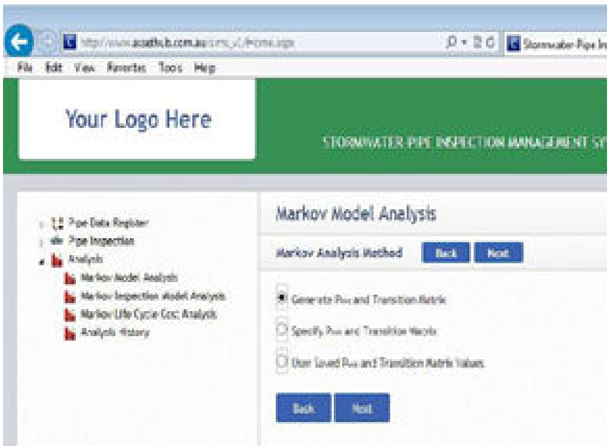

Figure 2c Options for Markov model

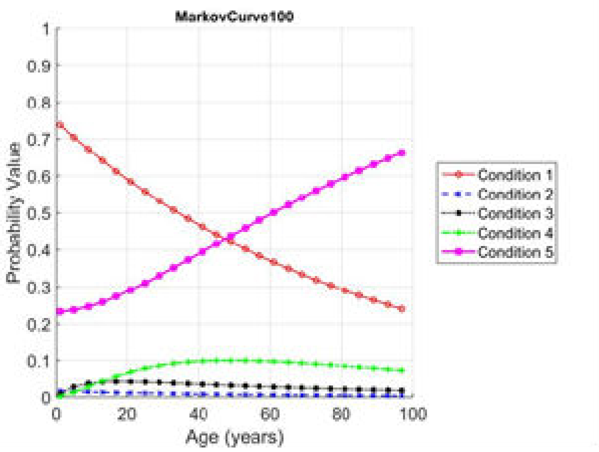

Figure 2d Result of Markov model

Figure 2d shows an example of a Markov model for structural deterioration of whole network. The interpretation is that if the average age of network is assumed 40 years as of 2015 (although individual pipes were installed in different past years), there are 45% of pipes in condition 1, 2% in condition 2, 5% in condition 3, 10% in condition 4 and 40% in condition 5. If pipe in condition 5 is valued as \$1 unit and condition 1 as \$5 unit, then the current valuation of pipe network can be estimated. Annual change of pipe condition and values and annual budget for maintenance can also be estimated for future years from the Figure 2d.

Run 'Markov Inspection Model Analysis'

The Markov Inspection Model is developed to estimate the next inspection time of a pipe with known current condition over a short planning horizon, which can be typically 10-20 years. The purpose of inspection is to detect pipes in poor condition for timing repair in order to avoid unexpected failure and to minimize annual cost. For this purpose, a penalty will be incurred if the inspection time is too long and thus fails to detect the poor condition. The optimal inspection time is estimated by using Monte Carlo simulation approach. In this approach, samplings of condition changes over the planning horizon are generated by Markov deterioration model. For each sampling, various inspection times are tried and associated cost are calculated in a process that stops when a poor condition is detected. Then average cost for each inspection time is taken over all samplings. The inspection time with minimal average cost is selected.

To run Markov Inspection Model Analysis for a pipe or a cohort, the selection of structural or hydraulic condition and then pipe filtering are first carried out in the same step as shown in Figure 2a and 2b of the Markov model. Figure 3a shows the required parameters. Figure 3b shows how annual cost rate varies with different inspection time and from there the optimal inspection time with minimal cost can be identified. Figure 3c shows that the longer the inspection time, the lower the cost but the higher the number of undetected poor conditions, which might require a compromise for risk-cost management.

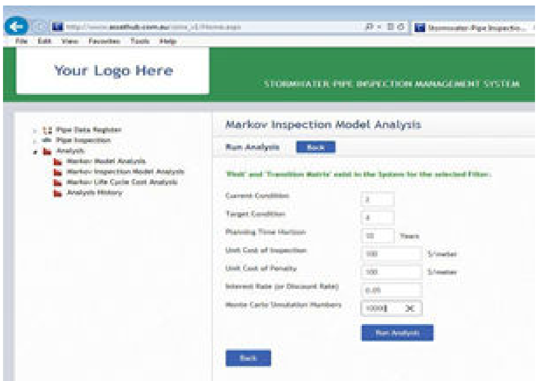

Figure 3a Required parameters of Markov inspection

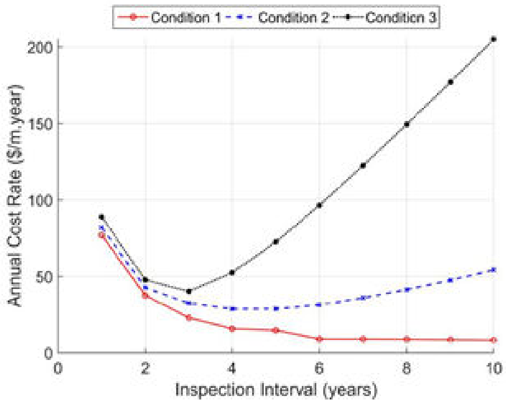

Figure 3b Optimal inspection time

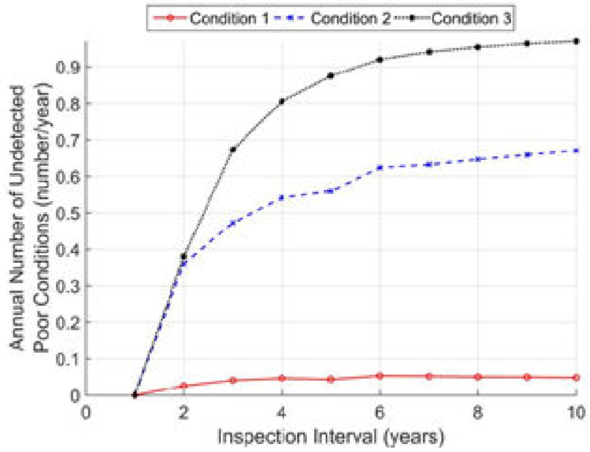

Figure 3c Number of undetected poor conditions

Run 'Markov LifeCycle Model Analysis'

The Markov LifeCycle Model is developed to estimate the lifecycle cost of inspection and repair for a pipe with known current condition over its expected service life time of typically 100 years. The lifecycle cost can be useful for budgeting and risk-cost mitigation.

For an inspection-based asset management strategy for stormwater pipes, the cost rate function (Hong et al., 2014) as shown in Equation 2 is utilized to determine the average cost per year over a planning horizon of T years.

$$CR(TI) = \left\{\sum_{i=1}^{ni} CI * e^{-\epsilon * i * TI} + \sum_{i=1}^{nm} CM * e^{-\epsilon * tMi} + \sum_{i=1}^{nf} CF * e^{-\epsilon * tFi}\right\}/T$$

where CR is cost rate (dollar/year), CI is unit inspection cost (dollar/unit length), CM is repair cost (dollar/ unit length), CF is replacement cost (dollar/ unit length), is interest rate with typical value of 5%, ni is number of inspection, nm is number of repair, nf is number of replacement, TI is inspection interval, tMi is time at the i^{th} repair, tFi is time at the i^{th} replacement, T is expected service life. The exponent function in Equation 2 transforms cost value in future time into cost value at present time using the concept of present value.

The lifecycle cost is estimated by using Monte Carlo simulation approach. In this approach, samplings of condition changes over the planning horizon are generated by Markov deterioration model. For each sampling, various inspection times are tried and associated costs are calculated in a process that replaces a failed pipe with a new pipe and repairs a poor condition to a better condition. Then average cost for each inspection time is taken over all samplings. The inspection time with minimal average cost is selected.

To run Markov Inspection Model Analysis for a pipe or a cohort, the selection of structural or hydraulic condition and then pipe filtering are first carried out in the same step as shown in Figure 2a and 2b of the Markov model. Figure 4a shows the required parameters.

Figure 4b shows how annual lifecycle cost varies with different inspection time and from there the optimal inspection time with minimal cost can be identified. Figure 4c shows that the longer the inspection time, the lower the cost but the higher the number of undetected poor conditions, which might require a compromise for risk-cost management.

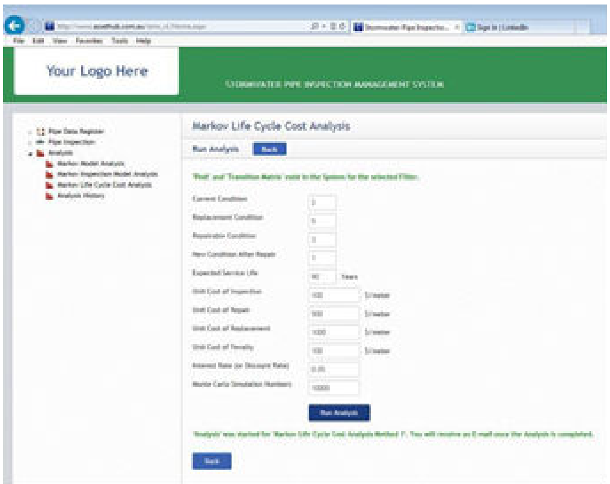

Figure 4a Required parameters of Markov lifecycle model

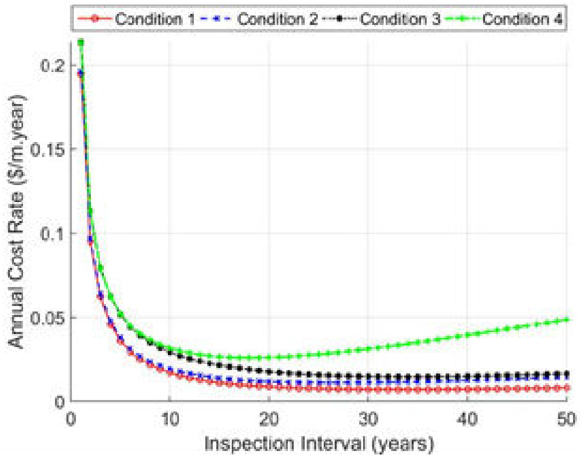

Figure 4b Optimal inspection time

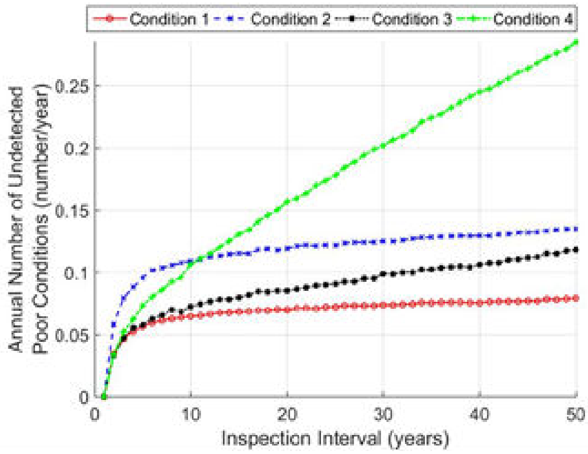

Figure 4c Number of undetected poor conditions

Run 'Markov Reliability Analysis'

The Markov Reliability Model is developed to estimate the time-dependent likelihood of failure (or failure probability) for both structural and hydraulic failure types and thereby allows estimating the remaining life 7

based on risk concept. The reliability of a structure is often assessed by establishing a limit state function

(G) which consists of the load or load effect (S) on the structure and the resistance of the structure (R) (Melchers, 1999).

$$G(X) = R-S \quad (3)$$

where X is a vector of random variables that define S and R in the n-dimensional space.

Mathematically, G(X) <0 or R<S indicates a failure domain. The failure probability Pf of the structure is then defined as:

Pf = probability [G(X) < 0]   (4)

The failure probability is estimated by using Monte Carlo simulation approach. In this approach, samplings of condition changes over the planning horizon are generated by Markov deterioration model. Sadiq et al. (2004) suggested to reduce tensile strength of cast iron pipes in proportion with decreasing pipe wall thickness due to pit corrosion. Based on their proposed idea, pipes with structural conditions from 1 to 5 can be assumed to have load bearing capacity Tp reduced by 0%, 7.5%, 15%, 22.5% and 30% respectively. Similarly, pipes with hydraulic conditions from 1 to 5 can be assumed to have pipe diameter reduced by 0%, 10%, 20%, 30% and 40% respectively. The threshold values of these assumptions for structural and hydraulic conditions can be adjusted with experimental or field testing. Time-dependent reliability assessment is conducted by varying pipe structural strength and hydraulic flow capacity as per the outcome from the Markov model. Values of remaining random variables affecting external structural and hydraulic loads on pipes are generated from their assumed distribution with constant means and coefficient of variation taking values between 0 and 0.4.

Figure 5 shows an example for calculating the probability of hydraulic failure for different variations of influential variables. As can be seen from the Figure, the probability of failure is increased over time due to pipe deterioration and change of influential variables. If the failure probability of 0.1 is considered high risk, then remaining life of pipes is 10 years for hydraulic failure.

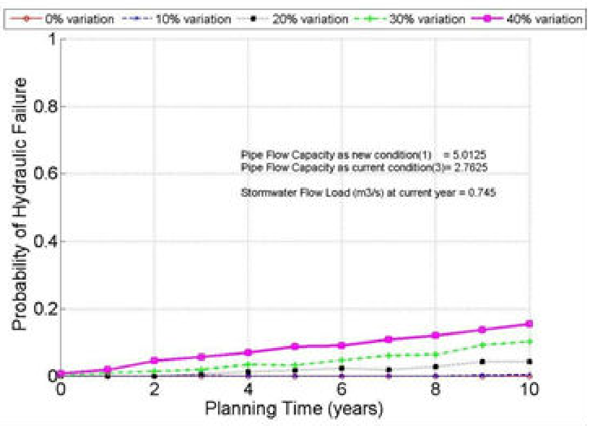

Figure 5 Example of probability of hydraulic failure

4. Discussion

The proposed AMF is considered a hybrid approach in which reactive management (i.e. wait to fail) is applied to non-critical pipes and proactive approach (i.e. regular inspection and repair) is applied to critical pipes. This approach is suitable for network of drainage stormwater pipes, whose failures are not frequent and catastrophic as compared to bridges and water mains and where budget is limited. SIMS provides an effective tool to understand and monitor risks and achieve optimal risk-cost management for the proposed AMF. However, SIMS requires accurate pipe data and sufficient inspection data, which are not always met by asset owners. For effective use of SIMS in the near future, the asset owners need to complete their data acquisition. A guide covering required data collection practices are currently being developed by the RMIT research team.

5. Conclusions

The paper presents an integrated asset management model for concrete storm water assets developed based on data collected by local councils in Victoria, Australia and the decision making practice adopted. The proposed methodology integrates data collected from CCTV inspections and pipe attributes. Whilst the full implementation of the model requires significant input data, the paper demonstrates the complete model with assumed input parameters for change in pipe strength and variability of condition data.

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