USING A MARKOV MODEL TO ESTIMATE PIPE DETERIORATION

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ABSTRACT

The Markov process is a mathematical model used to recreate stochastic systems which have the property of being "memory-less". That is; those systems for which the probability of being in any future state is dependent solely on the current state and not the past. These are often represented as two dimensional transition matrices indicating probability of going from one state to the next in one time period. Using a Markov process to model condition deterioration in pipes at first may seem counterintuitive. However there is some academic precedent for using Markov theory in pipe deterioration models (Kleiner *et al*. 2006).

Faced with limited known and traceable data on pipe condition in our networks, the Three Waters Asset Planning Team at Dunedin City Council (DCC) required a way to model deterioration for asset management purposes without any knowledge of condition history. A Markov process method was developed for estimating what was likely to happen based on what the current state was and how long the asset had to get to that state.

The method begins with breaking history into discrete periods. Assuming that a pipe is in condition 1 (excellent) when laid, all possible condition paths over those discrete time periods to the present day condition can be ascertained.

For example: if a pipe laid 4 time periods ago was now in condition 2 then there are 3 possible condition paths it may have taken: 1-1-1-2; 1-1-2-2; 1,2,2,2.

By taking a sample of pipes of the same material, laid at a similar time in history and assessing the individual conditions of all pipes in the sample, it is possible to estimate the probability of a given pipe being in a particular condition at the current time. Given that there are a finite number of paths to any one condition, the probability of each state to state transition in one time period can then be estimated.

Characteristic deterioration curves can be created based on weighting each path to the current condition by the probability of being in that condition at that point on the path. It has been these characteristic curves which have confirmed that this method captures known behaviour of certain pipe materials and therefore warrants further exploration.

KEYWORDS

Markov, Deterioration, Pipe Condition, Mathematical Modelling, Asset Management

1 INTRODUCTION

Faced with limited known and traceable data on pipe condition in our networks, the Three Waters Asset Planning Team at Dunedin City Council (DCC) required a way to model deterioration for asset management purposes without any knowledge of condition history. A Markov process is one in which the future state can be estimated based solely on the current state. Given that the actual conditions of our problem matched the key property of the Markov process, a Markov model was developed for estimating future condition based on current condition and the time in which the asset had to come to the current condition. Like all mathematical modelling this method is subject to verification and should also be tested for sensitivities. Initial indications are that there is significant validity to using this model for certain asset management decision making purposes – with the usual caveats on the use of models; such as: validity of the underlying assumptions, quality of input data and sensitivity to chosen parameters. In the absence of real data and the time and cost involved in acquiring the data, this model is shows promise of being an improvement on the current deterministic method of deterioration modelling.

2 MARKOV THEORY

Andrey Markov was a nineteenth century Russian mathematician known for his work with stochastic processes and is famous (in mathematical circles) for the particular process named after him. The Markov process is a mathematical model used to recreate stochastic systems which have the property of being "memory-less". That is; those systems for which the probability of being in any future state is dependent solely on the current state and not the past state. These processes are often represented as two dimensional transition matrices indicating probability of going from one state to the next in one time period.

2.1 RELEVANCE OF MODEL IN THIS APPLICATION

Using a Markov process to model condition deterioration in pipes at first may seem counterintuitive. However there is some academic precedent for using Markov theory in pipe deterioration models (Kleiner *et al.* 2006). In addition to this, there will be significant appeal for many asset managers to use this type of model as it is a common problem to need to estimate the future state of assets with little understanding of how they came to be in the place that they are currently.

Clearly pipe deterioration is not random in reality but is a function of a number of variables. However the identification and quantification of all these variables, in all applications, has proved elusive. There is a lack of availability of material-based pipe deterioration models that have uniform application, leaving each Asset Manager to assess the unique circumstances of each network or asset on a case by case basis. The problem is somewhat compounded for water pipes which cannot be readily condition assessed with the comparative ease of sewer assessments. Rather than expend energy, time and money into considering what might have been, bunching all possible causes together and defining them collectively as 'deterioration' – a random process in observation, and assigning probability to that deterioration, greatly enhances expediency. It is the expediency of a result that is the key justification to the DCC attempting to model pipe deterioration this way. An actual time history will take years to acquire, yet there is evidence that an improved decision making framework is required immediately. A model is always an unequal substitute for real information; however should that real information be unavailable or even not acquirable (for example; as it is in this case; lost in history) then it is likely to be the best option, at least in the interim.

3 DUNEDIN'S ISSUES

Dunedin's issues are common across most New Zealand territorial local authorities. However the urgency in treating some of these issues is likely to be greater for the DCC than many due to the age of the city and its infrastructure. The DCC has pipes well over one hundred years old in service but also has the looming Asbestos Cement (AC) renewals issue that is a common nationwide problem.

3.1 ASSET MANAGEMENT BEST PRACTICE

DCC Water and Waste Services Business Unit (WWSBU) has recently restructured and for the first time ever has a team dedicated to the strategic management of all its "Three Waters" assets. Historically a great deal of the asset management has been reactive. The City is also faced by a looming renewals peak, due to much of the city's pipe infrastructure approaching the end of its first lifecycle. Over the last year the new Three Waters Asset Planning team has been working to implement processes, in accordance with National Asset Management Steering (NAMS) Group best practice, to set up the WWSBU to work towards achieving advanced asset management practices and has made significant advances in understanding and rationalising the peak. However there is still a great deal to achieve and a significant lack of data with which to achieve it.

3.2 HISTORICAL LEGACY

DCC have been undertaking CCTV assessment of sewers for approximately twenty years. This has been mainly for determining causes of known problems rather than being part of a programmed condition assessment process. However, some condition data has been collected as a result. Most water pipe condition data (of which there is significantly less than sewer data) has been obtained in the process of maintenance. The DCC has current condition data on less than 4% of its buried assets. The data set should be considered as biased due to the reasons for which pipes were assessed being related to performance issues. The conditions are rated using the NAMS scale of 1 for excellent to 5 for failing. Until this point there has been no condition assessment schedule to identify and quantify physical condition criteria with each rating. This means that the current data is somewhat subjective and indeed there are ample cases of a pipe being graded as a 5 in one month and a 4 a few months later. This provides a source of weakness in this particular study however it can be rectified with the implementation of a complete set of condition grade criteria and a dedicated grading programme. A comprehensive condition assessment programme is being designed for all three waters assets and this will be driven by a newly implemented criticality assessment. The complete results will be unavailable for some time and a second round of assessment will need to occur in the future before the deterioration over time on a network basis can be accurately mapped.

3.3 ASBESTOS CEMENT VERSUS CAST IRON

The majority of Dunedin’s water network is either: Cast Iron (CI), Galvanised Iron (GI) or AC. Of particular importance is the anecdotal evidence that indicates that many AC pipes with long theoretical remaining lives will fail before Cast Iron (CI) pipes, which are already past their theoretical lives but haven’t yet been renewed. An age-based remaining life, which has historically been a key decision making criterion for renewals, means the DCC has been running the risk of renewing an operable CI pipe before a failing AC one, due to a lack of both current condition data and a clear understanding of failure likelihoods and therefore adequate risk assessment. An inability to quantify this anecdotal evidence is a hindrance to having confidence in a new renewals decision framework. Therefore the focus for this initial study was to compare Markov models for CI and AC water pipes to determine if this behaviour could be captured.

4 METHODOLOGY

The Markov property is valid for transitions over discrete time periods; therefore the first step to developing the model is to break history into discrete time periods. Decades are a suitable time period as a decade is enough time for a pipe to show differences in condition as well as being a large enough time step to not over complicate the modelling equations. Working back from the present (or from when the ‘current’ data was obtained) the number complete time steps that have occurred since the pipe was laid can be ascertained. Assuming that a pipe is in condition 1 (excellent) when laid, all possible condition paths over those time periods to the present day condition can be ascertained.

For example: a pipe laid in 1979 has had exactly three time periods elapsed since it was laid. If the pipe was now in condition 2 then there are 3 possible condition paths it may have taken: 1-1-1-2, 1-1-2-2, 1,2,2,2.

The more intervening time periods and the higher the current condition rating (5 being the worst) then the more possible paths there are. Enumerating all these paths is difficult and should be coded or created by some logic.[1]

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[1] . In this study VBA code in Excel was used.

A sample of same material pipes laid at a similar time in history will give a probability estimate of being in each of the current conditions at this age. Given that there are a finite number of paths to any one condition, the probability of each state to state transition in one time period can be estimated by creating a system of equations representing the sum of probabilities of all paths to each current condition. This is done by setting the sum of path probabilities to equal the sample condition probability and solving for the unknowns.

Let:

- the sample probability of a pipe laid X periods ago being in condition Y = PrX (Y)
- the probability of going from state i to state j in one time period is Pij where j <= Y

Then

- the probability of taking any path takes the form Π Pij - where i = the initial state to the second to last state in that path and j = the second state to the last state in that path.
- the total probability = Σ ΠPij = PrX(Y)

Using the above example: $Pr3\ (2) = (P11^2 \times P12) + (P11 \times P12 \times P22) + (Pr12 \times Pr22^2)$

If the number of independent samples was to be increased, then there would be a unique solution, by virtue of there being enough equations to match the unknowns (25). This would require a large amount of work in data collection and enumerating paths and would also restrict the availability of a 'free' sample to use for verification. In this study, two samples were used.

4.1 APPLICATION IN THIS STUDY

To further restrict the number of unknowns in the system of equations, it was assumed that condition grades could only remain the same or increase; that is; the pipes were assumed only to deteriorate. This assumption is only valid if the sample was not subject to repairs or rehabilitation. In the case of this study this assumption was not valid and some of the results are likely to be attributable to this. As the Markov property requires that probabilities are constant through time, including a probability for rehabilitation is also unrealistic because this would then allow for that probability at every step of the asset's life. As a consequence we can assume that a Markov model will over-estimate the condition of the pipe and the results will be skewed towards a lower rating or better condition than if the asset was simply allowed to deteriorate without intervention.

It was also assumed, given a lack of failure data from the sample's historical cohorts, that once condition five was attained, the pipe remained in this condition rather than failing.

These assumptions allowed the system to be simplified to nine unique equations (from the two samples) with fourteen unknowns.

A least squares optimisation using Excel solver was used to minimise the error in the estimation and provide a set of transition probabilities.

Resulting in a transition matrix of the form:

	1	**2**	**3**	**4**	**5**
1	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}

2	0	P_{22}	P_{23}	P_{24}	P_{25}
3	0	0	P_{33}	P_{34}	P_{35}
4	0	0	0	P_{44}	P_{45}
5	0	0	0	0	1

Table 1

As the purpose of this study was to investigate the suitability of such a model no time was spent in acquiring complete sets of random data. Rather, sample sets of data were taken from all pipes with known condition. This severely limited the data availability and indeed is not a random sample. There will be some inherent bias based on the reasons why condition data is held for these but not all assets. As outlined earlier, most condition data held for buried assets was acquired in the process of investigating operational problems or during repairs and maintenance. In order to achieve a large enough sample size, pipes from one or two years either side of the target year were included. Given that the 'current' data was in some cases several years old this was deemed appropriate if not ideal.

4.1.1 ASBESTOS CEMENT

AC pipes were laid between 1950 and 1975 in Dunedin. A sample from around 1955 (assumed to be five periods ago) and one from around 1975 (three periods ago) were found.

The samples yielded these condition probabilities

1955				
1	2	3	4	5
0	51%	16%	5%	27%
1975				
1	2	3	4	5
0%	76%	18%	0%	6%

Table 2: sample condition probabilities of AC pipes

A verification sample was chosen from around 1965.

4.1.2 CAST IRON

CI pipes were laid in Dunedin up until 1965. A sample from around 1935 (seven periods ago) and one from around 1945 (six periods ago) were found. There was not enough data at either end of the CI installation time line to use data from two significantly different periods.

A verification sample also from around 1965 was found – although this was a smaller sample than desired.

1935				
1	2	3	4	5

0%	35%	31%	29%	6%
1945				
1	2	3	4	5
0%	35%	35%	10%	20%

Table 3: Sample condition probabilities of CI pipes

5 RESULTS

Solving for the systems of equations resulted in the following transition matrices

AC	**1**	**2**	**3**	**4**	**5**
1	0.17	0.83	0	0	0
2	0	0.845	0.155	0	0
3	0	0	0.36	0.15	.49
4	0	0	0	.50	.50
5	0	0	0	0	1

Table 4: transition matrix for AC

CI	**1**	**2**	**3**	**4**	**5**
1	.48	.52	0	0	0
2	0	.80	.19	.01	0
3	0	0	.71	.22	.06
4	0	0	0	1	0
5	0	0	0	0	1

Table 5: transition matrix for CI

The most interesting aspects of these results are the high probability of AC staying in condition 2 until it deteriorates to condition 3 or 4 when probability of failing is around 50%. Also of note it is unlikely to achieve a grade 4 at all. In comparison the CI pipes show a tendency to remain in the same condition over a decade. There is a clear tendency to deteriorate slowly and consistently over time.

5.1 VERIFICATION

AC	Estimated	1965 Sample
1	0.001	0
2	0.63	0.75
3	0.18	0.18
4	0.04	0.04
5	0.16	.03

Table 6: Verification of AC results

CI	Estimated	1965 Sample
1	0.05	0
2	.58	.36
3	.27	.27
4	.09	.36
5	.01	0

Table 7: Verification of CI results

The verification samples tended to show good correlation towards the middle grade conditions but not at the extremes; under and over estimating good conditions and failing conditions. This is likely to be due to the invalid assumptions used in order to complete the model with the available data and inherent bias in the small non-random samples. There is also the likelihood that this model smoothes some effects over time. Removing the statistical bias would allow the determination of the presence of a smoothing effect. If indeed there is a smoothing effect it could be reduced or eliminated in a future version of the model by using a single period sample in the estimate. That is, when the DCC has a decade of condition data on a sample of assets, it can assess how much the model is reducing the impact of singular effects in one time period.

5.2 CHARACTERISTIC CURVES

Having constructed a transition matrix for each material pipe, characteristic curves can be created based on weighting each path to the current condition by the probability of being in that condition at that point on the path. These characteristic curves (Figure 1) would tend to indicate an overall smoothing effect in this model

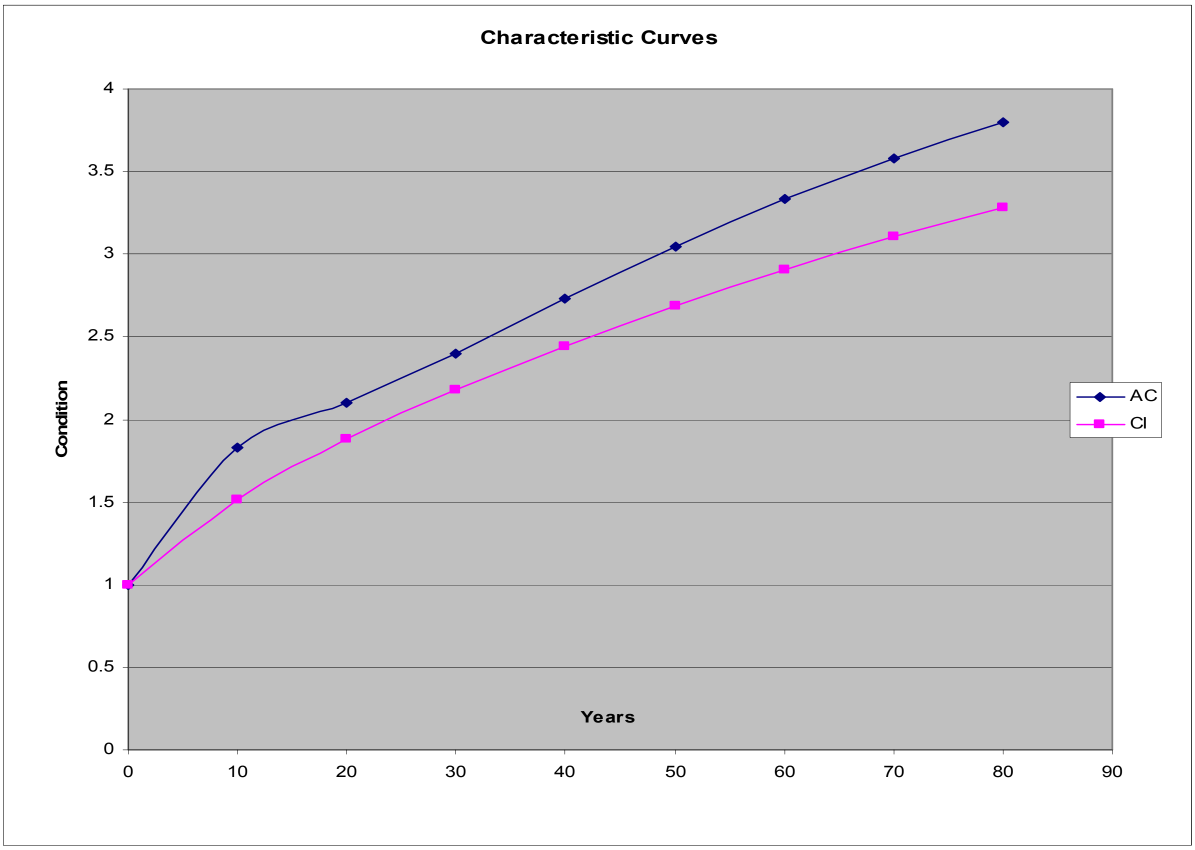

Figure 1 Characteristic Curves Achieved for AC and CI-SP

5.3 PROBABILITY CURVES

In addition to the deterioration curves, a probability distribution of the pipe condition given the age can be estimated without actually condition-assessing the pipe. This is useful for gaining an overview of the group of assets as a whole for risk profiling. Another application is for a condition estimation of non-critical assets for which actual condition assessment is expensive and the consequence of failure, should assessment be incorrect, is minimal

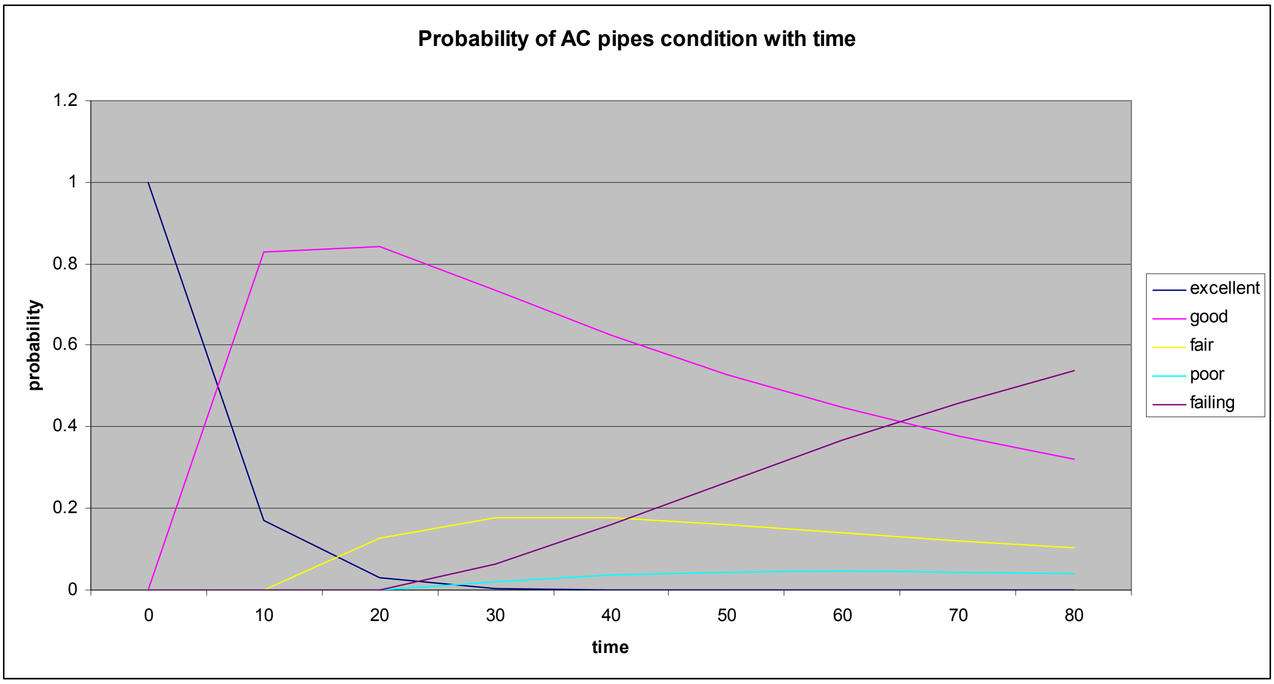

Figure 2: Probability Curves for AC condition

Of note in this graph is the equally likely outcomes of pipes being in good and failing condition at sixty five years old. This could be due to the over and under-estimations at the condition grade extremes in this model. However there is likely to be some validity in this estimate and this demonstrates the possibility of a large potential problem looming for the DCC in the next decade, as the first of the AC pipes laid in Dunedin are rapidly approaching that age.

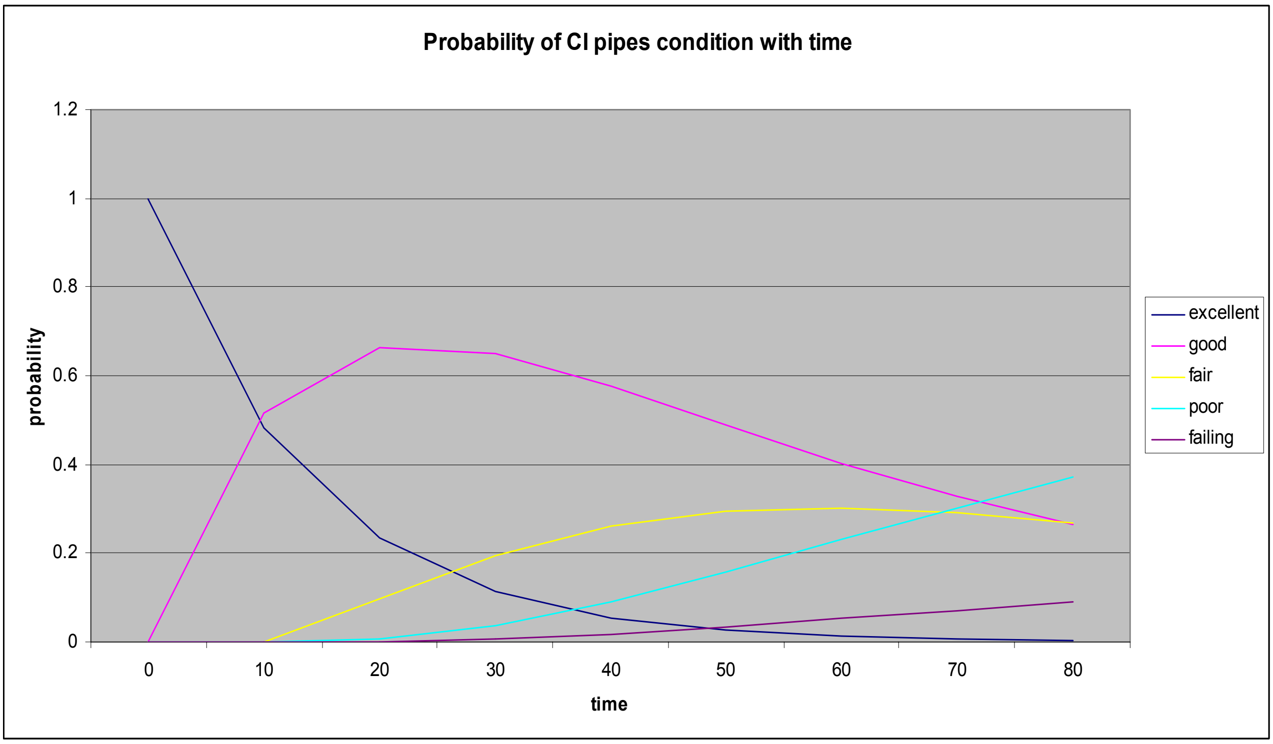

Figure 3: Probability Curves for CI-SP condition

This graph demonstrates what is being seen in Dunedin with CI pipes – that although significant numbers may be in poor condition, tuberculated and possibly service compromised – they are still very much operable in most cases. It is reasonable to expect that in the next decade that the majority of pipes in a condition grade of 3 or better will not only continue to operate but likely meet levels of service also. This outcome indicates it would not be overly risky to renew only the poorest condition pipes in this time.

6 CONCLUSIONS

Some worthwhile results have been achieved using a simplified version of the proposed methodology. Even when compromised by assumptions and raw input data with questionable validity the results appear to be useful. The models pick up some of the significant behaviours associated with CI and AC pipes. In particular these are: the increasing likelihood of AC failure after deterioration onset, the consistent deterioration over time of CI, and the high likelihood of CI pipes being fully operable at seventy-five years old. This adds great impetus to the anecdotal evidence available. One of the key indications derived is that there is significant risk in not renewing an AC pipe at condition grade 3 due to the likelihood of sudden failure. Yet a CI pipe which has already deteriorated to a poor condition may continue to operate for some time. There is clear relevance to a renewals decision making framework when comparing the two materials as these results highlight the differing approaches that will be required based on whether priority is given to level of service failure or criticality (consequence of engineering failure).

For these reasons, there is certainly a case for further investigation of the method. This study provides interesting if not conclusive results. Appropriate next steps would be to collect a truly random set of data and apply the methodology again to determine if the verification sample results improve. As the DCC continues to acquire actual condition data and also seeks specialist technical advice on actual pipe conditions and an engineering estimate of failure likelihood of those pipes, there will be increasingly relevant data that will allow the further improvement of this model.

Having started a condition assessment programme, the DCC can now track actual deterioration over time and create deterioration curves based on actual data. However it is infeasible to condition assess all pipes and it would seem relevant to continue to model deterioration in non-assessed pipes using the proposed methodology in order to create a complete risk profile and renewals forecast across all the networks.

Whilst this model may be a poor substitute to actual condition assessment and engineering failure estimation using technical measures, it shows the promise of being a useful additional tool in the absence of good real data.

REFERENCES

Kleiner Y, Rajani B, Sadiq R - “Modeling Deterioration and Managing Failure Risk of Buried Critical Infrastructure”: Institute for Research in Construction. National Research Council Canada. 2006