DEVELOPMENT OF PREDICTION MODELS FOR SEWER DETERIORATION

Prediction Models for Sewer Deterioration

D. M. ABRAHAM and R. WIRAHADIKUSUMAH
School of Civil Engineering, Purdue University, W. Lafayette, IN 47907, U.S.A.

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Abstract

Due to their low visibility, rehabilitation of sanitary sewers is often neglected until catastrophic failures occur. Neglecting regular maintenance of these underground utilities adds to life-cycle costs and liabilities, and in extreme cases, stoppage or reduction of vital services. Incorporating condition data and deterioration patterns of the city’s sewer system is pivotal for obtaining a realistic assessment of the city’s infrastructure. This paper will explore the probability-based Markovian approach for modeling deterioration. This approach is based on the assumption that since the behavior of sewer lines (i.e., the rate of deterioration) is probabilistic, the selection of an appropriate repair strategy is also an uncertain procedure. Probability-based prediction models enable the comparison of the expected proportions in given condition states with the actual proportions observed in the field, and in this way possible defects in construction, materials, quality control, etc., can be identified. Expert opinions from engineers, who have developed the sewer assessment surveys for the City of Indianapolis Department of Capital Asset Management (DCAM), will be used to validate the deterioration models developed in the research. More realistic deterioration models will assist asset managers in improved performance modeling of the sewer infrastructure and also in determining this infrastructure’s rehabilitation costs based on improved estimates of deterioration.

Keywords: deterioration, sewer systems, probabilistic methods, condition states, Markovian models, infrastructure, rehabilitation, maintenance

1 Introduction

The need to renew the deteriorating civil infrastructure in the U.S. creates a tremendous challenge to civil infrastructure system planners and managers in terms of financing, logistics, and demand and service assessment. Underground infrastructure such as sewer lines have to compete with other types of facilities for limited funds. Very often, maintenance of these facilities are neglected. Many of the nation's sewer systems are deteriorating and vulnerable to failure. Some failures can endanger public health and safety. Reactive maintenance strategies often result in difficult and costly rehabilitation (WEF-ASCE 1994). Tremendous capital can be protected if the cities could make better investment decisions and consider infrastructure management on a proactive basis.

Incorporating condition data and deterioration patterns of the city's sewer system is pivotal for obtaining a realistic assessment of the city's infrastructure. Deterioration models will assist asset managers in improved performance modeling of the sewer infrastructure and in determining this infrastructure's rehabilitation costs based on more realistic estimates of deterioration.

This paper will discuss the mechanisms of structural failures in sewers. An overview of prior research in the area of deterioration modeling for other infrastruture systems (e.g., bridges, pavements) will be provided. Finally, the use of Markov chain models for deterioration modeling of sewer systems will be described.

2 Deterioration in Sewer Systems

Sewer collapses are caused by hydraulic failures and structural failures. Hydraulic failures are caused by infiltration and inflow (I/I) problems. Infiltration is water that enters the system from the ground through pipe defects, while inflow is extraneous storm water that enters the system through roof leaders, direct stormwater connections, clean-outs, foundation drains, basement sump pumps, etc. These I/I problems reduce the planned hydraulic capacity of sewers, increasing the potential for collapse.

The intensity of structural failures depend on the size of defects, soil type, interior hydraulic regime, groundwater level and fluctuation, method of construction, and loading on sewers.

2.1 Materials

The stability of deteriorated sewers depends on the materials used for the construction of the sewer pipes. Rigid pipe materials are usually designed to resist vertical loading on their own, while brick sewers and flexible pipe materials require side support from the surrounding soil. Older sewers were typically constructed of vitrified clay, brick, or concrete. Presently, materials such as plastic, ductile iron, steel, reinforced concrete, reinforced fiberglass, etc., are used.

Extensive research projects which investigated all aspects of concrete and brick sewer system performance have been performed by Water Research Center (WRC) in order to understand the modes of failure for sewers (Serpente 1993). The research included field, laboratory, and theoretical studies. Two-hundred-and-fifty cases of sewer collapse were examined and mechanisms of ground loss and void formation were investigated. Based on these studies, it was found that the mortar and materials in pipe joints can be eroded, and corrosion in concrete sewers can occur due to the presence of hydrogen sulfide or other chemicals.

2.2 Soil conditions

The state of the surrounding soil is of great importance in assessing the structural condition of a sewer. The main factors that affect the rate of ground loss include sewer defect size, hydraulic conditions (water table, frequency and magnitude of surcharge), and soil properties (cohesive or non-cohesive soil). Severe defects (larger than 10 mm), high water table (above sewer level), frequent and high magnitude of hydraulic surcharge, and soil types: silts, silty fine sands, fine sands, can have serious effects on ground loss. Loss of side support will cause the side of the pipe to move outward when loaded vertically and collapse will be likely once the pipe deformation exceeds 10%. Uneven loading of pipes due to joint displacement also accelerates the pipe deterioration process.

3 Prior Research in Deterioration Modeling and Defects Analysis for Infrastructure Systems

Pavements and bridge assessment and deterioration models have been the basis for research in infrastructure systems.

3.1 Pavement Systems

Pavement deterioration models, currently in use, vary in complexity from simple straight-line extrapolation to probability models (Butt, et. al. 1994). However, when sufficient data are available, it is found that the shape of the deterioration curve is generally curvilinear rather than straight-line. Straight-line extrapolation tends to produce unrealistic results, while regression techniques are valid only if predictive variables that are related to condition deterioration can be found.

Probability-based Markov models have been used to portray the non-deterministic behavior of pavements. This form of predictive model has the advantage of ensuring that projections beyond the limits of data will continue to have the worsening pattern with age, something that regression models cannot guarantee (Butt, et. al. 1994). Other research studies on pavement deterioration models includes the utilization of latent variables to model characteristics that are not easily measurable or directly observable. Ben-Akiva and Gopinath (1995) propose a methodology that estimates deterioration using a latent dependent variable whose value is estimated from a set of indicators, which are measures of damage on the pavement. This modeling approach claims to have the flexibility to include different measurement techniques and data collection strategies.

3.2 Bridge Systems

Deterioration models developed for bridge systems include linear, piece-wise linear, linear regression coupled with a spike reflecting a single rehabilitation, non-linear regression with exponential decay functions coupled with spikes to reflect the effects of rehabilitation, and methods that incorporate Markov chain. Linear models do not provide sufficient accuracy, while the effort to develop the Markov chain requires an extensive database. Sanders and Zhang (1994) present deterioration models and modifications to databases that produce reasonable projections for bridge management systems that have limited data. Lu and Madanat (1994) have developed a method that employs condition data collected during facility inspections to improve the precision of deterioration models. The updating method used is a Bayesian approach, which combines prior information and sample information. This method decreases the level of uncertainty in forecasting the condition of bridge structures, and permits the development of a deterioration model even with limited data.

3.3 Sewer Systems

Several recent studies, including EPA (1991a), EPA (1991b) and ASCE (1989), have explored critical sewer management issues in order to provide information to support sanitary sewer infrastructure design and management. Dillard, Kurz and Stonecipher (1993) discuss the development of a defects classification system for sewers in order to provide objective criteria for evaluating most commonly observed defects and selecting proper rehabilitation measures. This classification system, used by the Metropolitan Department of Water and Sewerage Services (MWS) in Nashville, Tennessee, claims to improve correction of identified problems while minimizing their potential transfer to adjoining line segments.

Fick, Johnson and Johnson (1993) stress that effective management of urban infrastructure requires accurate assessment of system-wide condition. Their paper describes the development of a computer model to provide information about the overall condition of the sanitary sewer system and the associated costs of rehabilitation. The system developed by CH2M Hill in cooperation with the City of San Jose, California, provides an estimate of the system-wide condition through the inspection of only a fraction of the pipeline population. Sewer pipes are rated according to corrosion and structural conditions observed during closed-circuit TV (CCTV) inspections. However, the assessment is based primarily on the observed condition of the sewer system, and deterioration patterns are not considered.

Other work in the area of sanitary system assessment and management include the investigation of methods for collection of multi-sensory data for sewer inspection systems (Gokhale et. al. 1997, Abraham, et. al. 1997), and methods for automating the interpretation of the multisensory data (Wirahadikusumah, et. al. 1997). The understanding of sewer deterioration mechanisms helps asset managers in developing a prediction model by estimating whether a sewer has deteriorated sufficiently for collapse to be likely. One approach that has been successfully used in other types of infrastructure deterioration modeling is the Markov chain model. The following sections describe the initial results of the development and validation of a Markov chain model for predicting sewer deterioration.

4 Use of Markov Chain Model

Stochastic processes are processes that evolve over time in a probabilistic manner. In the sewer deterioration model, the stochastic processes $X_1, X_2, X_3, \ldots$ can represent the collection of condition ratings of a sewer line based on each five-year inspection data. At any time t, the condition of a sewer line can be described in exactly one of a finite number of mutually exclusive and exhaustive categories or *states.* In this case, five states (associated with condition ratings 1 to 5, with 1 being optimal sewer condition and 5 corresponding to critical sewer condition) are used.

A stochastic process is a Markov chain if it has the Markovian property, i.e., the conditional probability of any future event, given any past event and the present state $X_t = i$, is independent of the past event and depends only upon the present state. This property can be expressed as follows:

$$P\,(X_{t+1} = i_{t+1} \mid X_t = i_t, X_{t-1} = i_{t-1}, \ldots, X_1 = i_1, X_0 = i_0) = P\,(X_{t+1} = i_{t+1} \mid X_t = i_t) \qquad \ldots (1)$$

In order to reduce the complexity of the analysis, the future condition of sewers is assumed to depend only on the present state, and independent of the past condition. It is further assumed that for all states i and j and all t, $P(X_{t+1} = i_{t+1} \mid X_t = i_t)$ is independent of t. The probability, p_{ij}, that sewer condition is in state i at time t and it will be in a state j at time t+1 does not change (i.e., it remains stationary) over time (unless rehabilitation is performed, or other external factors change). This *stationary* assumption is expressed by equation (2).

$$P\,(X_{t+1} = j \mid X_t = i) = p_{ij} \qquad \text{... (2)}$$

The term *transition* is used when the system moves from state i during one period to state j during the next period. Accordingly, the probabilities, p_{ij}'s, are referred to as the *transition probabilities*. The transition probabilities are commonly displayed as an m x m matrix called the transition probability matrix P. In this study, there are five states associated with the five possible conditions of sewers (state 1 corresponds to the optimal condition and state 5 corresponds to the worst condition). To simplify the computation, it is assumed that sewer deteriorate by one state in one transition period. Thus, the transition probability matrix is given by:

$$P = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 & 0 \\ 0 & p_{22} & p_{23} & 0 & 0 \\ 0 & 0 & p_{33} & p_{34} & 0 \\ 0 & 0 & 0 & p_{44} & p_{45} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{... (3)}$$

The aforementioned transition probability matrix is for one-step (one-period) transition. The *n-step transition probability matrix*, $P^{(n)}$, of the process that is in state i and will be in state j after n periods (as opposed to in the *next* period) is computed using Chapman-Kolmogorov equation: $P^{(n)} = P^n$. The n-step transition probability matrix is then obtained by taking the n-th power of the one-step transition matrix (Ross 1997).

This Markovian model provides a reliable mechanism for developing prediction models. The Markov process imposes a rational structure on the deterioration model because it explains the deterioration as uncertain, and it also ensures that the projections beyond the limits of data will continue to have worsening condition pattern with age.

5 Example of Application

A significant requirement for the successful application of Markov chain model is the availability of reasonably good estimates of probability values in the transition matrices. These probability values can be estimated by analyzing deterioration curve for each sewer classification. These curves can be developed based on the historical records of sewer conditions, or based on expert opinions and assumptions.

In this study, expert opinions from the engineers who were instrumental in developing the sewer assessment surveys for the City of Indianapolis, Indiana, were used to estimate the probability values for the transition matrices. The study focused on large 60-inch (1500 mm) or larger combined sewers. For modeling purposes, the sewers were classified in terms of the following:

- Material: flexible sewers (brick, clay), rigid sewers (concrete, reinforced concrete)
- Ground water table (GWT): high ground water table (pipe crown is below GWT), low ground water table (pipe crown is above GWT)
- Soil type: cohesive soil, non-cohesive (granular) soil

- Depth cover: normal depth (between 3 feet (900 mm) and 20 feet (6000 mm), too shallow and under high live load (less than 3 feet (900 mm)) or too deep (more than 20 feet (6000 mm)).

Development of models for predicting deterioration in flexible sewers is discussed. The ideal conditions for flexible sewers are low ground water table, non-cohesive soil for backfill, and normal depth. Under these ideal conditions, the expected life of flexible sewers is about 100 years. The deterioration curve based on expert opinions for flexible sewers in ideal conditions is shown in Figure 1.

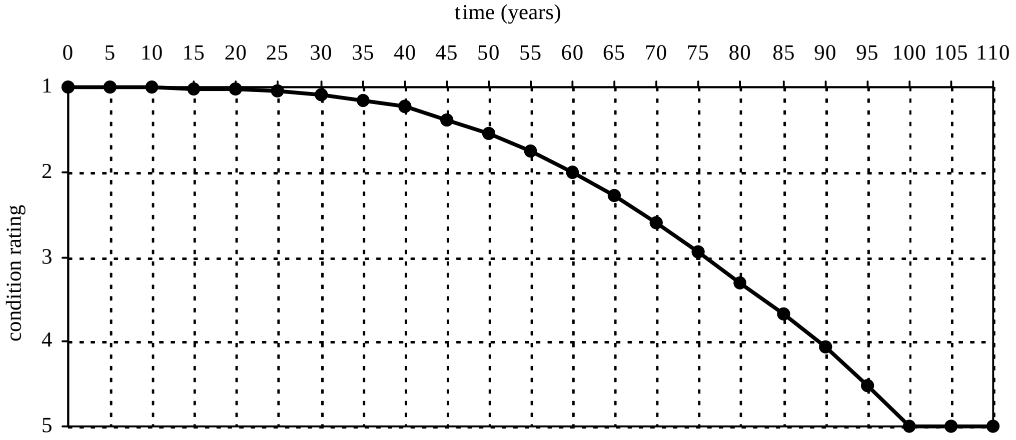


Figure 1: Deterioration curve of flexible sewers under ideal conditions

While flexible sewers in ideal conditions will reach their worst condition (rating 5) in 100 years, the expected life of similar sewers in adverse conditions such as very shallow depth cover, is decreased to about 90 years. However, the experts believe that the shape of the deterioration curve is unchanged. Table 1 shows the expected life of flexible sewers under different conditions, based on expert opinions.

Table 1: Expected life of flexible sewers

Soil type of backfill	Ground water table	Depth of cover	Expected life (years)
Non-cohesive	Low	Normal	100
Non-cohesive	Low	Too shallow or too deep	90
Non-cohesive	High	Normal	80
Non-cohesive	High	Too shallow or too deep	70
Cohesive	Low	Normal	65
Cohesive	Low	Too shallow or too deep	60
Cohesive	High	Normal	45
Cohesive	High	Too shallow or too deep	40

To estimate the probability values in transition matrices, a non-linear optimization technique is used to minimize the sum of absolute difference between the data points (from Figure 1) and the predicted condition for the corresponding age generated by the Markov chain model. The objective function of the non-linear optimization has the following form:

$$\text{Minimize} = \sum_{t=1}^{N} | Y(t) - E[X(t,P)] | \qquad \ldots (4)$$

where N = total number of periods
Y(t,j) = sewer condition data point at time t (from Figure 1)
E[X(t,P)] = expected value of sewer condition at time t as predicted by the Markov chain model with probability matrix P.

In this problem, the decision variable is the transition matrix P. As previously described, P is a 5x5 matrix as shown in (3). The expected condition of sewer at time t=n (which is in state 1 at time t=0), E[X(t=n,P)], is calculated using (5).

$$E[X(t=n,P)] = [1\ 0\ 0\ 0\ 0]\ P^{(n)}\ [1\ 2\ 3\ 4\ 5]^T \qquad \ldots (5)$$

To account for the assumption that older sewers would deteriorate faster, different transition matrices are used for every five-stage zone. By dividing the life of sewers into five-stage zones, there is an added advantage that the computation of the complex objective function shown in (4) becomes reasonably manageable.

Suppose the transition probability matrix for the first five stages (stage 0 to 5) is P and for the next five stages (stage 6 to 10) is Q. Then the expected condition of sewer at time t = 6 is estimated by

$$E[X(t=6,P)] = [1\ 0\ 0\ 0\ 0]\ P^{(5)}\ Q^{(1)}\ [1\ 2\ 3\ 4\ 5]^T \qquad \ldots (6)$$

As an example, consider flexible sewers in cohesive backfill, high ground water table, and deep cover. The transition matrices P and Q for such sewers that minimize equation (4) are shown in (7) and (8). Figure 2 shows the deterioration curve, as predicted by Markov chain model, for flexible sewers in such conditions. The expected life of such sewers is forty years.

$$P = \begin{bmatrix} 0.8500 & 0.1500 & 0 & 0 & 0 \\ 0 & 0.4696 & 0.5304 & 0 & 0 \\ 0 & 0 & 0.0001 & 0.9999 & 0 \\ 0 & 0 & 0 & 0.0001 & 0.9999 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots (7)$$

$$Q = \begin{bmatrix} 0.0001 & 0.9999 & 0 & 0 & 0 \\ 0 & 0.0001 & 0.9999 & 0 & 0 \\ 0 & 0 & 0.0001 & 0.9999 & 0 \\ 0 & 0 & 0 & 0.2462 & 0.7538 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots (8)$$

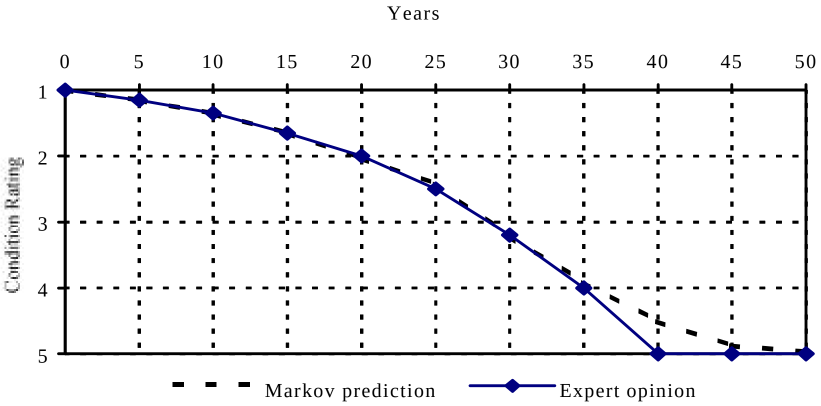


Fig. 2: Deterioration curve of flexible sewers in cohesive backfill, high ground water table, and deep cover.

The probability values in the transition matrices for flexible sewers in various conditions have been estimated using the same techniques. Table 2 lists the results and Figure 3 shows the comparison between deterioration curves based on expert opinions (3.a) and those developed by Markov chain models, computed with non-linear programming techniques (3.b).

Table 2: Estimated transition probabilities

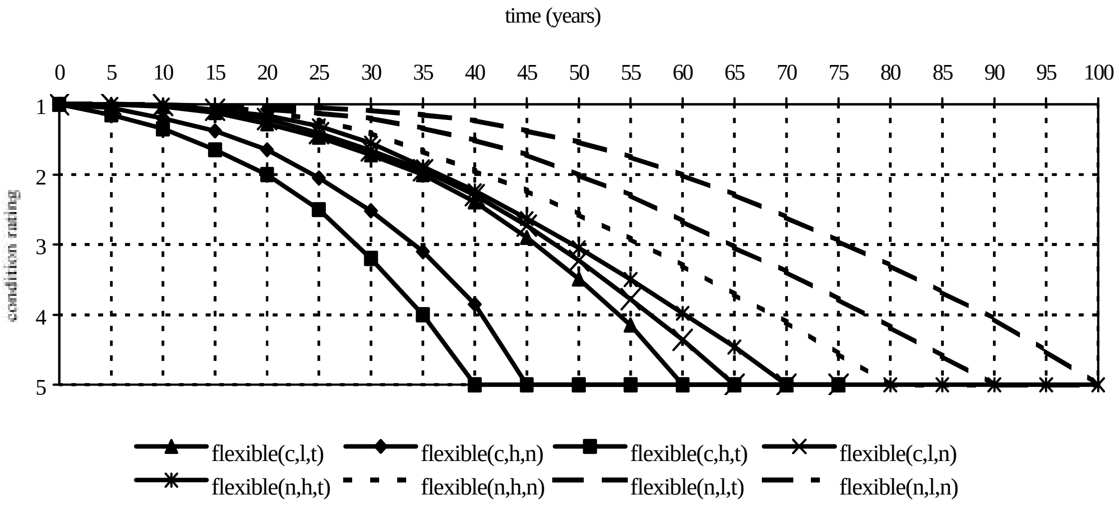
	cohesive, high, too deep expected life: 40 years				cohesive, high, normal depth expected life: 45 years			
	p_{11}	p_{22}	p_{33}	p_{44}	p_{11}	p_{22}	p_{33}	p_{44}
stage 1-5	0.8500	0.4696	0.0001	0.0001	0.9226	0.2567	0.0001	0.0001
stage 6-10	0.0001	0.0001	0.0001	0.2462	0.3671	0.1536	0.0001	0.0001

	cohesive, low, too deep expected life: 60 years				cohesive, low, normal depth expected life: 65 years			
	p_{11}	p_{22}	p_{33}	p_{44}	p_{11}	p_{22}	p_{33}	p_{44}
stage 1-5	0.9676	0.2917	0.0001	0.0001	0.9759	0.2929	0.0001	0.0001
stage 6-10	0.7523	0.4720	0.0001	0.0001	0.6943	0.6629	0.0972	0.0001
stage 11-15	0.0001	0.0001	0.0001	0.0001	0.0001	0.0845	0.0001	0.0001

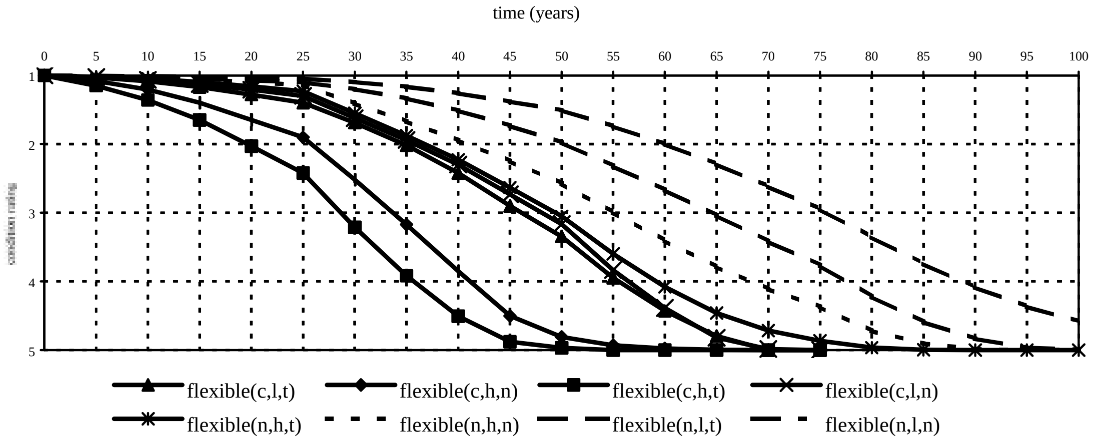
	non-cohesive, high, too deep expected life: 70 years				non-cohesive, high, normal depth expected life: 80 years			
	p_{11}	p_{22}	p_{33}	p_{44}	p_{11}	p_{22}	p_{33}	p_{44}
stage 1-5	0.9817	0.3011	0.0001	0.0001	0.9886	0.3073	0.0001	0.0001
stage 6-10	0.6845	0.6339	0.4410	0.0688	0.7347	0.7546	0.3819	0.4432
stage 11-15	0.2839	0.3125	0.3002	0.1962	0.5934	0.5548	0.4139	0.4124
stage16-20	N/A	N/A	N/A	N/A	0.0001	0.0001	0.0001	0.0001

	non-cohesive, low, too deep expected life: 90 years				non-cohesive, low, normal depth expected life: 100 years			
	p_{11}	p_{22}	p_{33}	p_{44}	p_{11}	p_{22}	p_{33}	p_{44}
stage 1-5	0.9920	0.3122	0.0001	0.0001	0.9957	0.5309	0.0001	0.0001
stage 6-10	0.9145	0.4786	0.1765	0.0001	0.9613	0.4460	0.0001	0.0001
stage 11-15	0.7383	0.4363	0.3193	0.0001	0.8138	0.4510	0.5250	0.0001
stage16-20	0.1947	0.0001	0.0001	0.0001	0.5345	0.3153	0.4130	0.3535

Deterioration curves developed by Markov chain model (Figure 3.b.) give good approximations to those obtained from expert opinions (Figure 3.a.). The application of Markov chain model in developing deterioration curves also ensures that the projections beyond the limits of data will continue to have worsening condition pattern with time.



(a) Based on expert opinions



(b) Markov chain model prediction

Fig. 3: Comparison of deterioration curves (Markov chain model vs. expert opinions)

6 Summary

Effective deterioration modeling will assist asset managers in improved performance modeling and more accurate prediction of the condition of sewer infrastructure, and will be a step towards preventive rather than reactive maintenance. This paper discussed the use of Markov chain models for developing deterioration models for flexible sewer systems under different soil and groundwater conditions. The deterioration curves developed closely resembled the curves obtained based on expert opinions. Future work will focus on integrating the deterioration models, with automated sewer condition assessment models, as well as with infrastructure management systems.

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8 References

Abraham, D. M., Iseley, T., Prasanth, R. K. and Wirahadikusumah, R. (1997). Integrating Sensing Technologies for Underground Utility Assessment. *ASCE Conference on Infrastructure Condition Assessment: Art, Science, Practice*, Boston, Massachusetts, August 1997, 316-325.

ASCE (1989). Sulfide in Wastewater Collection and Treatment Systems, *ASCE Manuals and Reports on Engineering Practice No. 69*, Joint Committee of the American Society of Civil Engineers and the Water Environment Federation, New York.

Ben-Akiva, M., Gopinath, D.(1995) Modeling Infrastructure Performance and User Costs. *ASCE Journal of Infrastructure Systems*, 1(1), 33-43.

Butt, A.A., Shahin, M.Y., Carpenter, S.H., and Carnahan, J.V. (1994) Application of Markov Process to Pavement Management Systems at Network Level. *Proceedings of The Third International Conference on Managing Pavements*, TRB-NRC, 159-172.

Dillard, C.W., Kurz, G.E., and Stonecipher, P.A. (1993) Management of Sewer System Rehabilitation for the Overflow Abatement Program in Nashville, Tennessee. *Proceedings of the International Conference on Pipeline Division of the ASCE*, San Antonio, Texas, 449-467.

EPA (1991a) *Handbook: Sewer System Infrastructure Analysis and Rehabilitation*, United States Environmental Protection Agency, 625/6-91/030.

EPA (1991b) Technology Transfer Seminars: Sewer System Infrastructure Analysis and Rehabilitation, United States Environmental Protection Agency, Cincinnati, Ohio.

Fick, B., Johnson, M., and Johnson J. (1993) Predictive Model Aids in Development of Systemwide Rehabilitation Program. *Proceedings of the International Conference of Pipeline Division of the ASCE*, San Antonio, Texas, 616-627.

Gokhale, S., Abraham, D. M., Iseley, T. (1997) Intelligent Sewer Condition Evaluation Technologies - An Analysis of Three Promising Options. *North American No-Dig '97 Conference*, Seattle, April 1997, 253-265.

Lu, Y. and Madanat, S. (1994) Bayesian Updating of Infrastructure Deterioration Models. *Transportation Research Record 1442*, Transportation Research Board - National Research Council, 110-114.

Ross, Sheldon M. (1997) *Introduction to Probability Models*, 6th edition, Academic Press.

Sanders, D. H. and Zhang, Y. J. (1994) Bridge Deterioration Models for States with Small Bridge Inventories. *Transportation Research Record*, 1442, 101-109.

Serpente, R. F. (1993) Understanding the Models of Failure for Sewers. *Proceedings of the International Conference on Pipeline Division of the ASCE*, San Antonio, Texas, August 1993, 86-100.

WEF-ASCE (1994) *Existing Sewer Evaluation and Rehabilitation*, ASCE Manuals and Reports on Engineering Practice, No. 62, Alexandria, Virginia.

Wirahadikusumah, R., Abraham, D. M., Iseley, T., Prasanth, R. K. (1997) Assessment Technologies for Sewer System Rehabilitation. *Journal of Automation in Construction*, 7(1998), 259-270.