OPTIMIZATION MODELING FOR SEWER NETWORK MANAGEMENT

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ABSTRACT: Due to their low visibility, sanitary sewers' condition assessment and rehabilitation are frequently neglected until a catastrophic failure occurs. Neglecting regular maintenance of these underground utilities adds to life-cycle costs and liabilities, and in extreme cases causes stoppage or reduction of vital services. A systematic approach for the determination of deterioration of sewer systems and an integrated management system are necessary to fully understand the complete status of this underground infrastructure system. This paper discusses the major aspects of integrated management for sewer systems, namely, the development of network identification, sewer classification and sewer condition rating systems, sewer deterioration mechanisms, prediction modeling, and the use of optimization techniques for maximizing benefit/cost ratios over a planning horizon. A case study, based on large combined sewers from the city of Indianapolis, has been used to demonstrate the use of the framework of this integrated life-cycle based sewer management system. Deterministic dynamic programming is employed to identify appropriate sewer rehabilitation techniques at different stages during the planning horizon adopted for the sewer systems.

INTRODUCTION

Historically, infrastructure rehabilitation has been prompted primarily by repairing failures rather than preventing them (*Fragile* 1988; U.S. Congress 1993; World Bank 1994). Traditionally, owners of underground infrastructure systems have approached the design, construction, maintenance, and operation of sewer systems with a crisis-based approach. As a result, the impact of important considerations such as construction practice, construction duration, life-cycle costs, legal and environmental impacts, safety requirements, public policy issues, etc., are not fully explored.

Asset managers in municipalities are frequently faced with budget-constrained situations. They are forced to address the problems of urban infrastructure as a system, and to recognize that the different components of the civil infrastructure are public assets, which need to be managed in order to achieve high returns on investment (Lemer 1996). There are many obstacles to achieving the greatest possible return on the public's assets. These include (1) the need to deal with multiple, often conflicting objectives; (2) the need to deal with uncertainties related to future decisions; (3) the lack of data (both qualitative and quantitative); (4) the need to incorporate the interests of diverse stakeholders; and (5) the need to account for the limitations posed by institutional and organizational structures (Lemer et al. 1995).

INTEGRATED SEWER MANAGEMENT SYSTEMS

A systematic approach for the determination of deterioration and obsolescence of underground infrastructure (and in particular, sewer systems) and an integrated sewer management system are necessary to fully understand the complete status of this underground infrastructure system. A well-defined integrated sewer management system includes, but is not limited to, routine and systematic sewer structural and hydraulic condition assessments, establishment of a standard condition rating system, developing and updating prediction models for sewer performance, life-cycle cost analysis, and development of prioritization schemes for selection of rehabilitation options.

This paper discusses the major aspects of integrated management for sewer systems, namely, the development of network identification, sewer classification and sewer condition rating systems, sewer deterioration mechanisms, prediction modeling, and the use of optimization techniques for maximizing benefit/cost ratios over a planning horizon (as shown in Fig. 1).

The proposed integrated sewer management system provides guidelines in the decision-making processes, because it uses optimization techniques to obtain minimum cost of maintenance/rehabilitation strategies over the life cycle of sewer systems. The current condition of sewers will be evaluated and future conditions of the sewer system will be predicted in this life-cycle approach. By taking into account future conditions as a consequence of present rehabilitation action, the best alternative, as well as the priority and schedule of rehabilitation, are determined.

DEVELOPMENT OF NETWORK IDENTIFICATION AND SEWER CLASSIFICATION

The first step in setting up a sewer management system is to "divide" the sewer system into separate smaller networks so that each network can be stored in a single database to provide efficient data entry and report generation. Some of the factors to consider when identifying different networks are use (sanitary, storm, combined, or process sewers), location/zone, and any other distinctive criteria (funding source, required condition, etc.). An example of a smaller network for separate inspection and analysis in the city of Indianapolis's sewer system is "combined sewers of 150 cm (60 in.) diameter or larger." This network, consisting of approximately 108 km (360,000 ft) of sewers is identified based on its distinctive properties: combined sewers and large diameter. The characteristics of this network have been recorded in a database including its condition assessment, which was based on walk-through (person-in-pipe) and remote-controlled closed-circuit television (CCTV) inspections.

Once the networks are identified, they are defined by "sewer runs" and "sewer segments." The city of Indianapolis refers to a "sewer run" as a manageable group of sewer segments sorted from an upstream manhole to the furthest downstream manhole of a basin, and is labeled after the street name above the pipelines and the basin number. A "sewer segment" is viewed as the smallest management unit when considering the application and selection of rehabilitation strategies. A sewer

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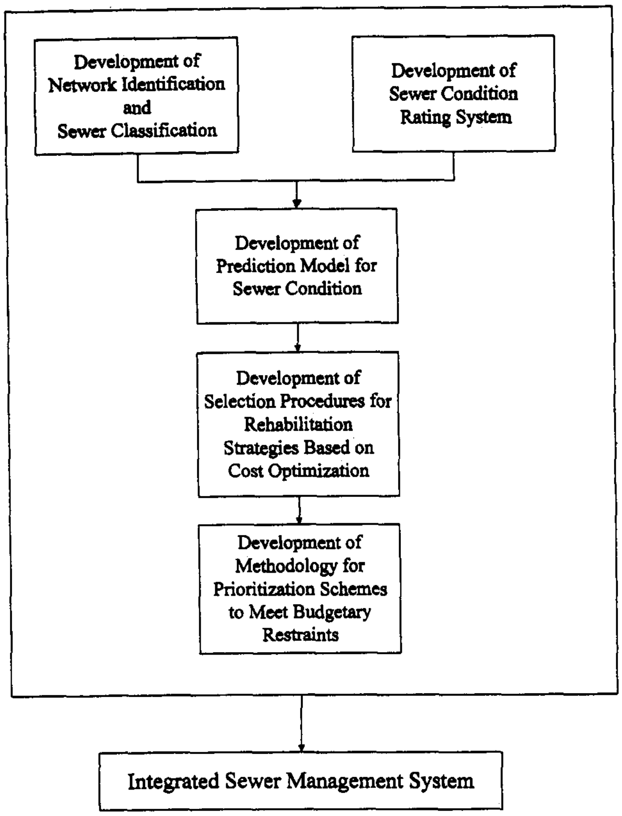

FIG. 1. Major Components of Integrated Sewer Management System

segment is defined as a pipeline and its upstream manhole (Greeley and Hansen 1996).

Sewers are then classified into different categories to account for differences in material, diameter, etc., and to account for changes in condition characteristics and deterioration mechanisms. Condition rating systems and deterioration models need to be developed for every classification of sewers. Sewer segment classification should be based on common characteristics, such as sewer structure (clay, brick, concrete, plastic, etc.), diameter, and environmental conditions that contribute to sewer deterioration (infiltration, depth of cover, etc.). Good examples of sewer classification systems and the corresponding sources of deterioration are discussed in "Handbook" (1991) and Water (1994).

DEVELOPMENT OF SEWER CONDITION RATING

The goal of a condition rating system is to objectively rate, by means of a scoring system, the current condition of the infrastructure. In the field of pavement management, the Pavement Condition Index (PCI) developed by the U.S. Army Corps of Engineers has received wide acceptance and has been formally adopted as standard procedure by many highway agencies. The PCI is a numerical index, ranging from 0 for a failed pavement to 100 for a pavement in excellent condition. The degree of pavement deterioration is a function of distress type, distress severity, and amount or density of distress. Assigning one index that considers the three factors is difficult, so "deduct values" are introduced as a type of weighting factor to account for effects caused by each combination of distress type, severity level, and distress density. Based on in-depth knowledge of pavement behavior, input from many experienced pavement engineers, field testing and evaluation of the procedure, and accurate descriptions of distress type, severity levels and their corresponding deduct values were derived to develop a composite distress index, the PCI (Shahin 1994).

No such standard procedure has been developed for sewer systems. A key reason could be a lack of linkages between the sewer systems maintained and managed by the different municipalities, unlike the manner of the management of highways by the different states.

While standard procedures for developing comprehensive sewer condition ratings (similar to PCI) do not exist, some rating systems have been developed by certain municipalities in the United States. Dillard et al. (1993) discuss the development of an identification and classification system to provide objective criteria for evaluating most commonly observed defects and selecting proper rehabilitation measures in sewer systems. This system for defect classification and ratings has been used by Metro Nashville Department of Water and Sewerage Services, and it incorporates local experience and identification criteria reported in the literature. The sewer condition is rated based on general defect criteria including crack patterns (hairline, radial, or transverse), causes of inflow/infiltration (joint, crack, or service lateral), joint conditions (separated, protruding, or dropped gasket), service lateral conditions (protruding, defective, root infested, or inflow/infiltration), degree of root intrusions (light, medium, or heavy) and structural defects (pieces missing, sagging, collapsing, or crushed). The rating factors range from 0 to 9. Observance of a hairline crack is rated 0, while structural defects such as holes in pipe (pipe pieces missing) and a crushed pipe are rated 9. The condition for root intrusions is rated as light, medium, or heavy. Because the rating for root intrusions is very subjective, the evaluation of root conditions is standardized by reference illustrations and photographs.

Fick et al. (1993) explain the development of a computer model, developed by CH2M Hill for the city of San Jose, Calif., to provide information on a macro level about the overall condition of the sanitary sewer systems and the associated costs of rehabilitation. The model provides an estimate of systemwide condition through the inspection of a fraction of the city's pipeline. The condition assessment model estimates the overall condition of the wastewater collection system based on CCTV inspection data for a random sample of sanitary sewer pipes. The data, along with other attributes, such as pipe material, age, and location, are analyzed to assess the condition of the pipes that were not inspected.

The sewer condition rating system developed for the city of San Jose is based on three factors: corrosion condition, structural condition, and impact factors. The corrosion conditions are categorized as light, medium, severe, or soil exposed. Structural defects include cracks, fractures, breaks, deformities, collapses, holes, root, infiltration, debris, alignment, and open and offset joints. The first two factors do not quantify potential impacts of pipeline failure, so an impact factor is used to provide a relative scale to account for pipeline conditions not directly documented by CCTV inspection. This impact factor is a function of pipeline location, loads due to traffic environment, and size of pipe.

The city of Indianapolis's sewer condition rating for its large combined sewer system is based on walk-through inspections and on pan-and-tilt TV inspections of sewers with flows too high be be safely inspected by walk-through inspections. Inspection forms were used to record the structural defects in each sewer segment. For concrete pipe, the defects include cracking, deflection, corrosion, and subsidence, while for brick pipe the structural defects include cracking, deflection, missing bricks, and dropped invert. Each type of defect is scored 0 for "no visible sign," 1 for "little evidence," 2 for "average evidence," and 3 for "high evidence." The aggregate score is then used to produce a Sewer Condition Rating with 1 signifying optimal condition and 5 signifying critical condition.

The information from sewer inspections is then combined

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with any applicable internal factors of the pipe (e.g., signs of infiltration, evidence of surcharge) and external factors (e.g., soil type, ground-water depth above the sewer invert, and depth of cover) to adjust the sewer condition rating. The adjusted sewer condition rating is called the overall structural grade. Sewer sections with overall structural grades of 4 and 5 are the candidates for rehabilitation. Because it is more cost-effective to rehabilitate entire sewer runs than to rehabilitate individual sewer segments, priority ratings of sewer runs are developed. Based on cost-effectiveness, installation issues, impact on sewer hydraulics, and material and durability issues, a list of high priority sewer runs, including the selected rehabilitation alternatives, is compiled (Greeley and Hansen 1996; Short 1997).

SEWER DETERIORATION MECHANISMS

Sewer collapses are caused by structural and hydraulic failures. The intensity of structural failures depends on the size of the defect, soil type, interior hydraulic regime, ground-water level and fluctuation, corrosion, method of construction, and loading on a sewer. 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 storm-water 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 stability of deteriorated sewers depends on the materials used for the construction of the sewer pipe. 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, new materials are used such as plastic, ductile iron, steel, reinforced concrete, and reinforced fiberglass.

Extensive research projects that 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 investigations on mechanisms of ground loss and void formation were performed. 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.

The state of the surrounding soil is of fundamental 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, and frequency and magnitude of surcharge), and soil properties (cohesive or noncohesive 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, and fine sands) can have serious effects on ground loss. Loss of side support will allow 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.

DEVELOPMENT OF PREDICTION MODEL FOR SEWER CONDITION

A comprehensive study performed by WRC (Serpente 1993) concluded that the concept of measuring the "rate of deterioration" of sewer is unrealistic since deterioration is more influenced by random events in a sewer life span (such as a storm or an excavation nearby) and severe defects do not always lead immediately to collapse. However, while it may be impossible to predict when a sewer will collapse, it is feasible to estimate whether a sewer has deteriorated sufficiently for collapse to be likely.

Assessment and deterioration models for pavements and bridges (Butt et al. 1987; Jiang et al. 1988; Ben-Akiva and Ramaswamy 1993; Butt et al.. 1994; Lu and Madanat 1994; Ben-Akiva and Gopinath 1995) have been the primary focus for research in infrastructure systems. Although many of the concepts developed for these systems have been domain dependent, prior research in assessment and deterioration of these systems is also reviewed to explore the possibility of either adoption or adaptation of existing models and methodologies for the development of a prediction model for sewer systems.

Prediction models currently used for predicting the performance of infrastructure systems (in particular, pavement systems) include straight-line extrapolation, regression techniques, and the probability-based Markovian model (Butt et al. 1994). Straight-line extrapolation tends to produce unrealistic results, while regression techniques are valid only if the predictive variables can be found that are related to condition deterioration.

Probability-Based Markovian Models

Markovian models provide a reliable mechanism for developing prediction models. Markov chains can be employed to model stochastic processes, which have the distinct property that probabilities involving how the process will evolve in the future depend only on the present state of the process and so are independent of events in the past (Hillier and Lieberman 1995). The model development is restricted to Markov chains that have (1) a finite number of states; and (2) stationary transition probabilities (i.e., transition probabilities that do not change in time).

The Markov process imposes a rational structure on the deterioration model because it explains the rate of deterioration as uncertain, and it also ensures that the projections beyond the limits of data will continue to have a worsening condition pattern with time. This model has been successfully used in other types of infrastructure deterioration modeling.

A Markov chain approach analogous to that which has been developed for pavement deterioration modeling (Butt et al. 1994) can be applied to sewer systems. To model the manner in which a sewer deteriorates with time, it is necessary to establish a Markov probability transition matrix. The transition matrix $\mathbf{P}$ is a square matrix, $m \times m$, where m is the number of possible states. Thus, if there are five categories in sewer conditions, then five possible states will be involved in the matrix of size 5×5. The components of $\mathbf{P}$, namely p_{ij}, are the probabilities of being in state i at time 0 and transitioning to state j over a given period Δt. A time increment, Δt, of 5 yr is suitable because sewer inspections should generally be conducted every 5 yr. If the assumption is accepted that the sewer condition will not drop by more than one state in any 5-yr period, then the condition will either stay in its current state or move to the next lower state in 5 yr. Therefore, the one-step transition matrix can be represented as follows:

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 & 0 \\ 0 & p_{22} & p_{23} & 0 & 0 \\ 0 & 0 & p_{33} & p_{34} & 0 \\ 0 & 0 & 0 & p_{44} & p_{45} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

For each row of the transition matrix, $\Sigma_j\, p_{ij} = 1$. The value

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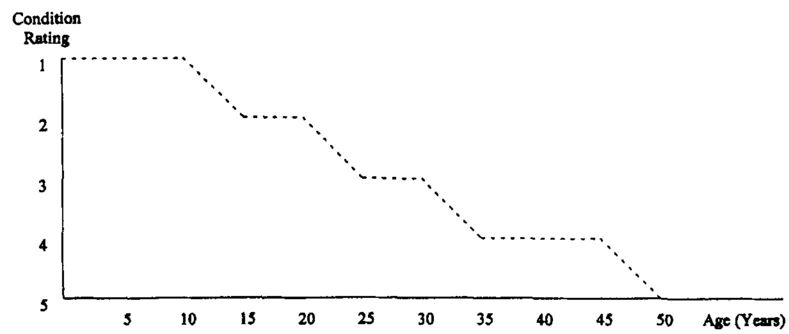

FIG. 2. Deterministic Prediction Model for Typical Sewers

of 1 in the last row indicates an "absorbing" state corresponding to the fact that the sewer condition cannot move from this state (the worst possible state) unless rehabilitation is performed. In this particular transition matrix, the values of four unknown quantities (i.e., p_{11}, p_{22}, p_{33}, and p_{44}) have to be determined. The application of the Markov process (Butt et al. 1994) proposes a nonlinear programming approach to determine the probability values by minimizing the sum of the absolute difference between actual data points and the predicted condition for the corresponding time generated by the Markov chain.

The probability that the sewer is in state i at time $t = t$ and will be in state j after n periods is desired. Chapman-Kolmogorov equations provide a method for computing the n-step transition probabilities, and the n-step transition probability matrix can be obtained by computing the nth power of the one-step transition matrix (Hillier and Lieberman 1995). Thus, if the one-step transition matrix $\mathbf{P}$ corresponds to a 5-yr time period, then the two-step (10-yr time period) transition matrix $\mathbf{P}^{(2)}$ is represented by

$$\mathbf{P}^{(2)} = \mathbf{P}^2 = \mathbf{P} \times \mathbf{P}$$

Besides the transition matrix $\mathbf{P}$, the state matrix $\mathbf{X}$ representing the probability distribution of being in m different states at time 0 (which is the fraction of sewer network currently in each of the m possible states) is also required. $\mathbf{X}$ is a single-row matrix (or state vector) where $\Sigma X_i = 1$ for $i = 1, \ldots, m$. The state vector for any time cycle t is obtained by multiplying the initial state vector by the transition matrix $\mathbf{P}$ raised to the power of t. Thus, the prediction of sewer condition 10 yr from now is then represented by $\mathbf{X}^{(2)}$.

$$[\mathbf{X}^{(2)}] = [\mathbf{X}] \times [\mathbf{P}^{(2)}]$$

The use of the Markov chain prediction model is sufficient to formulate the problem as a dynamic programming problem because the knowledge of the current state of the system conveys all the information about its previous behavior necessary for determining the optimal policy henceforth. This property is required in dynamic programming formulation (Hillier and Lieberman 1995). The application of the Markov chain prediction model in conjunction with dynamic programming has several advantages. It uses objective condition measures and has computational efficiency in handling a large number of rehabilitation strategies for each sewer classification/state combination. However, the model development requires sufficient statistical data for establishing sound transition probability matrices.

Deterministic Model

The previously described probabilistic approach is scientifically more appropriate to model the stochastic nature of deterioration of infrastructure because it is inherently uncertain. However, the condition of sewer pipelines in most cities is generally not fully documented. Only 14% of the cities surveyed by Malik et al. (1997) have any kind of sewer condition data on their infrastructure information systems.

When historical condition data are not readily available, the use of deterministic dynamic programming together with a heuristic prediction model based on expert opinion is suggested. The relationship between sewer condition and its age for typical large concrete/brick sewers can be described, as shown in Fig. 2. In this case, the condition of a sewer system deteriorates over its service time from its optimal condition (rated 1) to its worst condition (rated 5) if no maintenance/rehabilitation work is implemented. The relationship between sewer age and condition is assumed to behave as described in Fig. 2 when asset managers apply the "do nothing" strategy throughout its service time. The expected service time of 50 yr is considered appropriate. After 50 yr, sewers tend to be in critical condition, because of the higher likelihood of collapse.

SELECTION OF SEWER REHABILITATION OPTIONS

Fig. 3 shows the selection process of sewer rehabilitation alternatives that has been adopted by the city of Indianapolis (for its large combined sewers). Four alternatives were considered for rehabilitation of large combined sewers: shotcrete, cured-in-place pipe, sliplining with fiberglass reinforced pipe liner, and dig-and-replace with reinforced concrete pipe.

Shotcrete is typically the lowest cost alternative and provides good structural support. However, bypass of the wastewater is required and the workers have to work in confined spaces for extensive hours. Because shotcreted pipes have little resistance to chemical attack, this alternative is not feasible if the existing pipe shows signs of corrosion.

The cured-in-place pipe (CIPP) lining process involves the insertion of a flexible lining into the sewer, using an inversion process with in-situ curing. The lining consists of a polyester bag, impregnated with a thermosetting polyester or epoxy resin. The lining is inserted through the existing manholes under pressure of water and is later cured by circulating hot water (larger pipe diameters are inverted and cured using hot air). The ends are cut and sealed. Service connections are localized and reestablished by cutting the line with special instruments guided by CCTV. CIPP has approximately 50 yr of expected service life and has strong resistance to chemical attack. The disadvantages include the requirement for bypass pumping, requirement of excavation at insertion manholes, and high initial cost.

Sliplining with fiberglass reinforced pipe starts with cleaning of roots, solids, and protrusions from the existing pipe. The fiberglass-reinforced pipe can be inserted either by pushing or by pulling it into place. This technique requires excavation of insertion pits and involves some confined space entry. A high initial cost can be justified based on the manufacturer's claim that this relatively new material is expected to provide more than 100 yr of service life.

The method of dig-and-replace with reinforced concrete

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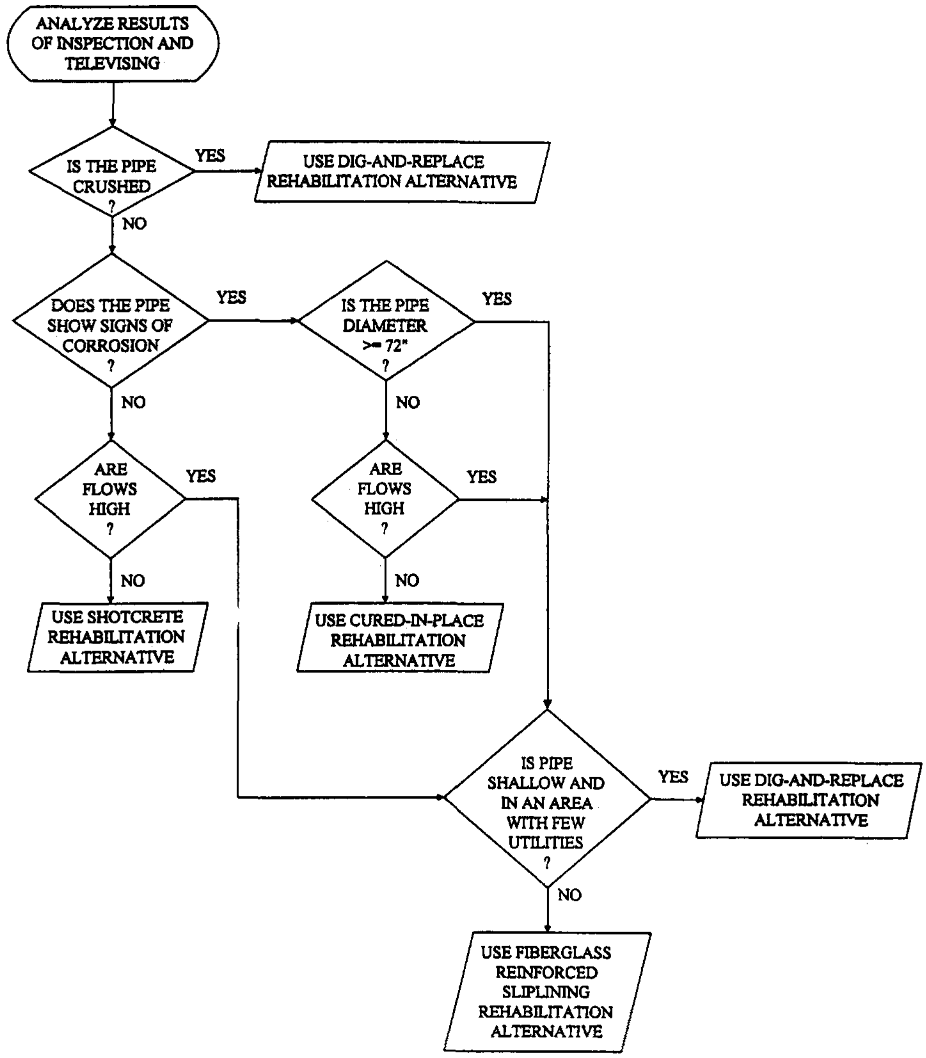

FIG. 3. Selection Process of Sewer Rehabilitation Alternatives (Greeley and Hansen 1996)

pipe requires excavation, which may cause disruptions. It may also involve bypass pumping, and is a time consuming and labor intensive activity. If the existing pipe is crushed, then dig-and-replace with reinforced concrete is the preferred alternative.

While installation issues, impact on hydraulics, and material and durability issues are key factors in the selection process, the decision tree (shown in Fig. 3) does not explicitly include life-cycle cost issues associated with each alternative. The process does not attempt to predict future sewer conditions, and accordingly life-cycle analysis is not performed. This is mainly due to immediate goals to minimize initial project cost in order to meet budgetary restraints, the lack of historical sewer condition data, and the lack of accepted industry standards for describing the life-cycle behavior of the sewer systems. These constraints affect effective decision making regarding infrastructure rehabilitation in many municipalities across the United States.

LIFE-CYCLE COST ANALYSIS OF SEWER REHABILITATION

An approach that predicts the future condition of sewers is needed to perform life-cycle cost analysis for different sewer rehabilitation options. Deterministic prediction models similar to that shown in Fig. 2 can be incorporated with dynamic programming for life-cycle cost analysis of sewer systems. For a given planning horizon, the proposed dynamic programming technique provides suggestions to decision makers by optimizing total cost (or maximizing benefit/cost ratio) of sewer system. The total cost includes construction costs, maintenance and rehabilitation costs, and intangible (such as disruption) costs, based on predicted levels of future condition. The output of this technique is the optimal maintenance/rehabilitation strategy (i.e., the minimum life-cycle cost strategy) and the scheduled time of application for each sewer segment. The accumulation of the optimum costs for all sewer segments within a network gives the total maintenance and rehabilitation costs needed for the entire sewer network. If there are delays in rehabilitation on particular sewer segments, the associated consequences can also be estimated.

As in most other cities, historical data on sewer condition are not readily available in the city of Indianapolis. Since a realistic probability-based analysis cannot be performed at this time, a deterministic dynamic programming approach is developed for optimization of the sewer network management. Invaluable input was obtained from the city of Indianapolis's engineering consultants and from the analysis of its large [150 cm (60 in.) or larger in diameter] combined sewer rehabilitation alternatives.

Assumptions

The basic features that characterize the deterministic dynamic programming optimization model for management of a brick or concrete sewer system are defined as follows:

1. The planning horizon can be divided into *stages*, with a

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decision required at each stage. Each stage represents a 5-yr time segment in the planning horizon of 50 yr. The 5-yr time segment is related to the recommended time interval of sewer inspections, and the 50-yr planning horizon is chosen because the expected design life of typical large sewers (e.g., concrete or brick) is at least 50 yr. In this case, the stages are stage 0, 1, . . . , 10.

2. Each stage has a number of *states* associated with the beginning of that stage. The states associated with each stage in the sewer management problem are the states of sewer conditions with rating 1, 2, 3, 4, or 5 (5 being the worst, i.e., pipe crushed, and 1 relating to optimal condition). Hence, states 1, 2, 3, 4, and 5 are associated with condition ratings 1, 2, 3, 4, and 5, respectively.
3. At each stage, the *decision variables* represent different types of feasible rehabilitation strategies that are applicable to each sewer segment. In this example, five rehabilitation options are considered: shotcrete, CIPP, sliplining with reinforced fiberglass pipe liner, dig-and-replace with concrete pipe, and "do nothing."
4. Shotcrete coating is not recommended in cases where the sewer is subject to internal corrosion. CIPP, sliplining, and pipe replacement can be applied otherwise. Sewers in state 5 (crushed pipe) can only be rehabilitated with the dig-and-replace alternative. Sewers in states 1 or 2 are typically not rehabilitated. Sewers in state 3 are usually not treated unless a sewer segment in state 3 is physically located in between segments in states 4 or 5. Once a sewer is in state 4, the "do nothing" option is no longer appropriate.

   Thus, for typical sewers, feasible rehabilitation strategies for each state are as follows:
   - State 1: do nothing
   - State 2: do nothing
   - State 3: do nothing
   - State 4: shotcrete, CIPP, reinforced fiberglass sliplining, or dig-and-replace with concrete pipe
   - State 5: dig-and-replace with concrete pipe

   Routine maintenance (inspection and cleaning every 5 yr) can be applied after sewers have been rehabilitated to their optimal conditions, which are obtained when the sewer lines are either replaced or rehabilitated using the CIPP alternative or the sliplining alternative.
5. Representative unit costs of each rehabilitation option for

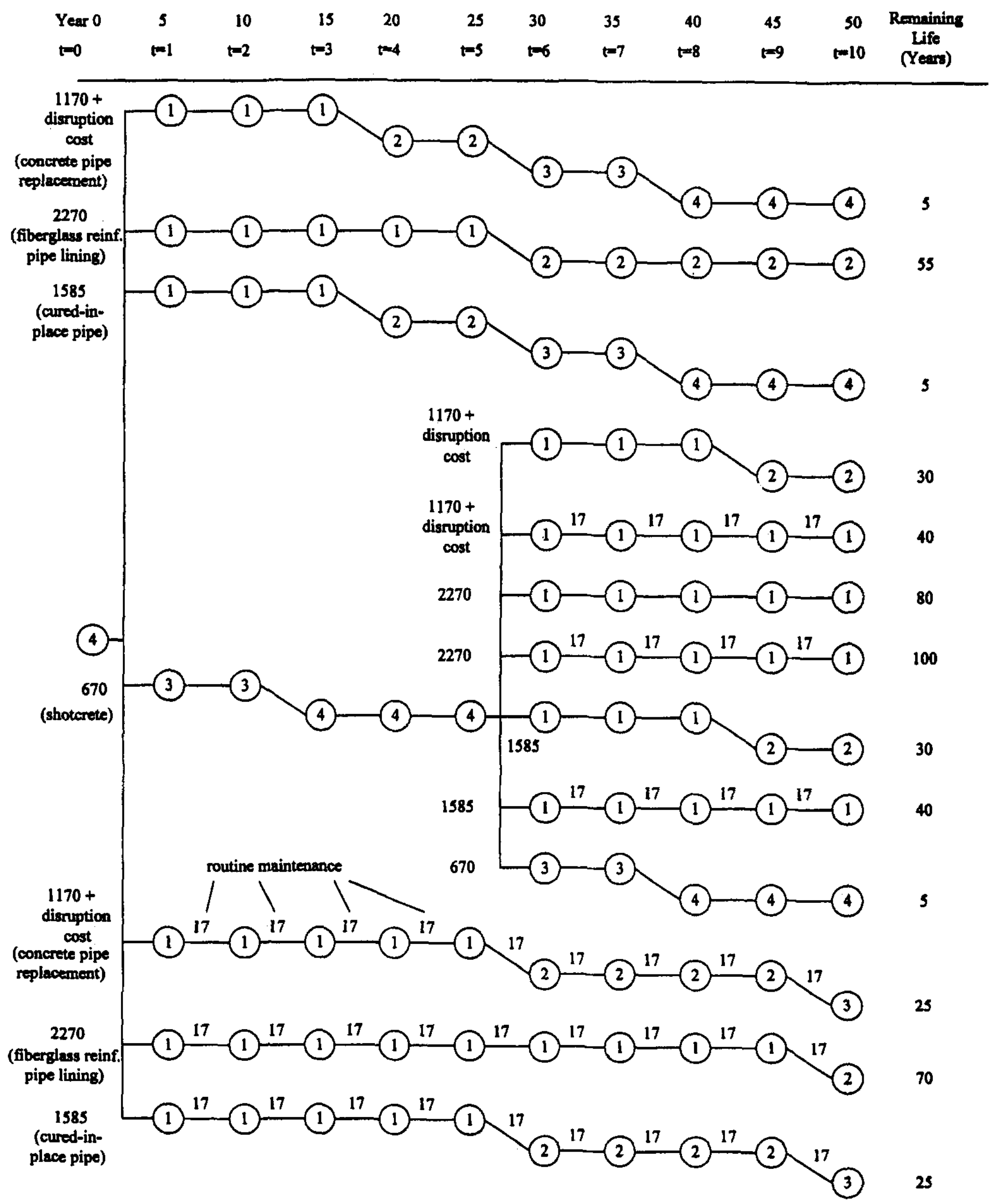

FIG. 4. Network Formulation for Sewers in State 4

a large 150-cm- (60-in.-) diameter sewer in the Indianapolis area are as follows:
- Shotcrete: $670/m ($200/ft)
- CIPP: $1,585/m ($475/ft)
- Reinforced fiberglass sliplining: $2,270/m ($680/ft)
- Dig-and-replace with concrete pipe: $1,170/m ($350/ft) + disruption cost
- Routine maintenance: $17/m ($5/ft)
- "Do nothing": $0/m

Disruption costs are intangible costs that have to be considered when replacing sewer pipes. These costs depend on the location of sewers (rural area versus downtown area, under a busy street, etc.) as well as on the existence of other utility facilities in areas under the influence of the sewers.

6. Engineering judgment is required to determine the degree of improvement in the sewer condition after certain rehabilitation options have been utilized. For the purpose of this model, it is assumed that shotcreting extends the life of sewers by 20 yr, which translates to improving condition by one state (e.g., from state 4 to state 3), and CIPP treatment changes the sewer condition by three states (e.g., from state 4 to state 1) because it extends sewer life for 50 years. The expected service life of reinforced fiberglass lining is greater than 100 yr. Replacement with concrete pipe would change the sewer condition from state 5 to state 1 and would extend sewer life for 50 years. The "do nothing" strategy would cause the sewers to deteriorate in a pattern similar to that modeled in Fig. 2.
7. The objective function involves the maximization of the benefit/cost ratio of the maintenance and rehabilitation treatments over the life cycle of the sewer. The primary benefit associated with applying a certain rehabilitation treatment to a specific sewer segment is its extended life (e.g., shotcreting is assumed to prolong sewer life 20 years, while fiberglass reinforced pipe lining could extend its life to 100 yr). The expected remaining service life of the sewers at the end of planning horizon is the estimated "salvage value." The present value method with interest and inflation rates is applied to account for the time value of money associated with the life-cycle cost analysis.
8. Every state of sewer condition is formulated as a network. Fig. 4 shows an example of the dynamic programming network for sewers in state 4. This technique solves the problem by finding optimal path(s), which gives the maximum benefit/cost ratio of rehabilitation strategy. The problem is solved step-by-step by first suboptimizing the last component, then suboptimizing the last two components, and so on until the whole network is optimized.

EXAMPLE OF APPLICATION

Based on a recent condition assessment project, Sewer Segment No. 251068, which is a 150-m- (500-ft-) long, 150-cm- (60-in.-) diameter concrete pipe, is in state 4. This particular segment is recommended for rehabilitation because state 3 is the City of Indianapolis's minimum acceptable condition level. Four rehabilitation options are considered by the asset manager: shotcrete, CIPP, sliplining with fiberglass reinforced pipe, and dig-and-replace with concrete pipe. Routine maintenance (inspection and cleaning every 5 yr) is also an option once the sewer segment is rehabilitated to state 1. Table 1 shows the cost and benefit of each rehabilitation option.

The cost of replacement with concrete pipe also includes costs to account for the disruptions that may be incurred when

TABLE 1. Costs and Benefits of Maintenance/Rehabilitation Options for Sewer Segment No. 251068

Rehabilitation option (1)	Cost (dollars/m) (2)	Benefit (yr) (3)
1. Shotcrete	670	20
2. CIPP	1,585	50
3. Fiberglass reinforced pipe lining	2,270	100
4. Replacement with concrete pipe	1,170 + disruption cost	50
5. Routine maintenance (inspection and cleaning every 5 yr)	17	10–20

TABLE 2. Benefit/Cost Ratio Calculations for Sewer Segment No. 251068 (Inflation and Discount Rates not Applied)

Rehabilitation strategy (1)	Treatment Costs in Year t: Year 0 (dollars/m) (2)	Year 5 (dollars/m) (3)	Year 10 (dollars/m) (4)	Year 15 (dollars/m) (5)	Year 20 (dollars/m) (6)	Year 25 (dollars/m) (7)	Year 30 (dollars/m) (8)	Year 35 (dollars/m) (9)	Year 40 (dollars/m) (10)	Year 45 (dollars/m) (11)	Benefit (remaining life), year 50 (yr) (12)	Total cost, year 25–45 (dollars/m) (13)	B/C ratio (14)	Total cost (dollars/m) (15)	B/C ratio (16)
1. Concrete pipe replacement	1,670	—	—	—	—	—	—	—	—	—	5	—	—	1,670	0.003
2. Reinforced fiberglass sliplining	2,270	—	—	—	—	—	—	—	—	—	55	—	—	2,270	0.024
3. CIPP	1,585	—	—	—	—	—	—	—	—	—	5	—	—	1,585	0.003
4a. Shotcrete—concrete pipe replacement	670	—	—	—	—	1,670	—	—	—	—	30	1,670	0.018	—	—
4b. And inspection and cleaning	670	—	—	—	—	1,670	17	17	17	17	40	1,738	0.023	—	—
4c. Shotcrete—reinforced fiberglass sliplining	670	—	—	—	—	2,270	—	—	—	—	80	2,270	0.035	—	—
4d. And inspection and cleaning	670	—	—	—	—	2,270	17	17	17	17	100	2,338	0.043	3,008	0.033
4e. Shotcrete—CIPP	670	—	—	—	—	1,585	—	—	—	—	30	1,585	0.019	—	—
4f. And inspection and cleaning	670	—	—	—	—	1,585	17	17	17	17	40	1,653	0.024	—	—
4g. Shotcrete—shotcrete	670	—	—	—	—	670	—	—	—	—	5	670	0.007	—	—
5. Concrete pipe replacement and inspection and cleaning every 5 yr	1,670	17	17	17	17	17	17	17	17	17	25	—	—	1,823	0.014
6. Reinforced fiberglass sliplining and inspection and cleaning every 5 year	2,270	17	17	17	17	17	17	17	17	17	70	—	—	2,423	0.029
7. CIPP and inspection and cleaning every 5 yr	1,585	17	17	17	17	17	17	17	17	17	25	—	—	1,738	0.014

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such segments and other neighboring utility lines have to be taken out of service. The estimated additional cost is \$500/m (\$150/ft), bringing the total cost of replacement with concrete pipe to \$1,670/m (\$500/ft). For the sake of simplicity, inflation and discount rates are ignored in this example.

The formulation of the network model for Sewer Segment No. 251068 is similar to that shown in Fig. 4. The calculation of the maximum benefit/cost ratio is illustrated in Table 2. The maximum benefit/cost ratio is provided by shotcreting the segment at current stage (sometime between year 0 and 5), slip-

TABLE 3. Benefit/Cost Ratio Calculations for Sewer Segment No. 251068 (Inflation Rate = 3%/yr; Discount Rate = 5%/yr)

Rehabilitation strategy (1)	Treatment Costs in Year *t*										Benefit (remaining life), year 50 (yr) (12)	PV at 25 total cost, year 25–45 (dollars/m) (13)	B/C ratio (14)	PV at 0 total cost (dollars/m) (15)	B/C ratio (16)
	Year 0 (dollars/m) (2)	Year 5 (dollars/m) (3)	Year 10 (dollars/m) (4)	Year 15 (dollars/m) (5)	Year 20 (dollars/m) (6)	Year 25 (dollars/m) (7)	Year 30 (dollars/m) (8)	Year 35 (dollars/m) (9)	Year 40 (dollars/m) (10)	Year 45 (dollars/m) (11)					
1. Concrete pipe replacement	1,670	—	—	—	—	—	—	—	—	—	5	—	—	1,670	0.003
2. Reinforced fiberglass sliplining	2,270	—	—	—	—	—	—	—	—	—	55	—	—	2,270	0.024
3. CIPP	1,585	—	—	—	—	—	—	—	—	—	5	—	—	1,585	0.003
4a. Shotcrete—concrete pipe replacement	670	—	—	—	—	3,497	—	—	—	—	30	3,497	0.009	—	—
4b. And inspection and cleaning	670	—	—	—	—	3,497	41	48	55	64	40	3,609	0.011	—	—
4c. Shotcrete—reinforced fiberglass sliplining	670	—	—	—	—	4,753	—	—	—	—	80	4,753	0.017	—	—
4d. And inspection and cleaning	670	—	—	—	—	4,753	41	48	55	64	100	4,865	0.021	2,107	0.047
4e. Shotcrete—CIPP	670	—	—	—	—	3,319	—	—	—	—	30	3,319	0.009	—	—
4f. And inspection and cleaning	670	—	—	—	—	3,319	41	48	55	64	40	3,431	0.012	—	—
4g. Shotcrete—shotcrete	670	—	—	—	—	1,403	—	—	—	—	5	1,403	0.004	—	—
5. Concrete pipe replacement and inspection and cleaning every 5 yr	1,670	20	23	26	31	36	41	48	55	64	25	—	—	1,768	0.014
6. Reinforced fiberglass sliplining and inspection and cleaning every 5 yr	2,270	20	23	26	31	36	41	48	55	64	70	—	—	2,614	0.027
7. CIPP and inspection and cleaning every 5 yr	1,585	20	23	26	31	36	41	48	55	64	25	—	—	1,894	0.013

TABLE 4. Benefit/Cost Ratio Calculations for Sewer Segment No. 251068 (Shotcrete Is not Feasible; No Inflation and No Discount Rates Applied)

Rehabilitation strategy (1)	Treatment Costs in Year *t*										Benefit (remaining life), year 50 (yr) (12)	Total cost (dollars/m) (13)	B/C ratio (14)
	Year 0 (dollars/m) (2)	Year 5 (dollars/m) (3)	Year 10 (dollars/m) (4)	Year 15 (dollars/m) (5)	Year 20 (dollars/m) (6)	Year 25 (dollars/m) (7)	Year 30 (dollars/m) (8)	Year 35 (dollars/m) (9)	Year 40 (dollars/m) (10)	Year 45 (dollars/m) (11)			
1. Concrete pipe replacement	1,670	—	—	—	—	—	—	—	—	—	5	1,670	0.003
2. Reinforced fiberglass sliplining	2,270	—	—	—	—	—	—	—	—	—	55	2,270	0.024
3. CIPP	1,585	—	—	—	—	—	—	—	—	—	5	1,585	0.003
4. Concrete pipe replacement and inspection and cleaning every 5 yr	1,670	17	17	17	17	17	17	17	17	17	25	1,823	0.014
5. Reinforced fiberglass sliplining and inspection and cleaning every 5 yr	2,270	17	17	17	17	17	17	17	17	17	70	2,423	0.029
6. CIPP and inspection and cleaning every 5 yr	1,585	17	17	17	17	17	17	17	17	17	25	1,738	0.014

TABLE 5. Benefit/Cost Ratio Calculation for Sewer Segment No. 251068 (Shotcrete Is not Feasible; Inflation Rate = 3%/yr; Discount Rate = 5%/yr)

Rehabilitation strategy (1)	Treatment Costs in Year *t*										Benefit (remaining life), year 50 (yr) (12)	PV at 0 total cost (dollars/m) (13)	B/C ratio (14)
	Year 0 (dollars/m) (2)	Year 5 (dollars/m) (3)	Year 10 (dollars/m) (4)	Year 15 (dollars/m) (5)	Year 20 (dollars/m) (6)	Year 25 (dollars/m) (7)	Year 30 (dollars/m) (8)	Year 35 (dollars/m) (9)	Year 40 (dollars/m) (10)	Year 45 (dollars/m) (11)			
1. Concrete pipe replacement	1,670	—	—	—	—	—	—	—	—	—	5	1,670	0.003
2. Reinforced fiberglass sliplining	2,270	—	—	—	—	—	—	—	—	—	55	2,270	0.024
3. CIPP	1,585	—	—	—	—	—	—	—	—	—	5	1,585	0.003
4. Concrete pipe replacement and inspection and cleaning every 5 yr	1,670	20	23	26	31	36	41	48	55	64	25	1,768	0.014
5. Reinforced fiberglass sliplining and inspection and cleaning every 5 yr	2,270	20	23	26	31	36	41	48	55	64	70	2,368	0,030
6. CIPP and inspection and cleaning every 5 yr	1,585	20	23	26	31	36	41	48	55	64	25	1,683	0.015

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lining with reinforced fiberglass at year 25, and then inspecting/cleaning the sewer every 5 yr (maintenance/rehabilitation strategy 4d).

If the decision maker expects an annual inflation rate of 3% and a discount rate of 5% for the next 50 yr, rehabilitation strategy 4d remains optimal (see Table 3). This optimal rehabilitation strategy involves shotcrete application at current stage. However, this option is not feasible if the pipe shows signs of corrosion, because a shotcreted pipe with no additional treatment would have very little resistance to chemical attack. When rehabilitation options exclude shotcreting, the calculation in Table 4 suggests the adoption of reinforced fiberglass sliplining and inspection/cleaning every 5 yr thereafter. This treatment requires higher initial cost but its life-cycle benefit/cost ratio is the highest. Reinforced fiberglass sliplining with regular inspection/cleaning also remains optimal when inflation (3%) and discount (5%) rates are applied (see Table 5).

Sensitivity analysis that accounts for changes in the estimated remaining life of the sewer at the end of year 50, as well as changes in disruption costs, should also be explored so that decisions can be made appropriately.

SUMMARY

This paper discusses the development of prediction models—both probability-based and deterministic—for sewer deterioration analysis. The probability-based model provides a reliable method to characterize the uncertainty inherent in sewer deterioration. When sufficient data to perform the probability-based prediction model are not readily available, the deterministic approach is deemed acceptable. Both models can be incorporated with dynamic programming as an optimization technique to maximize the benefit/cost ratio. The described dynamic programming is unconstrained. If the aggregate cost over all sewer segments within a network is higher than the available budget, then a prioritization scheme needs to be developed.

Numerous options are available for sewer rehabilitation. Some techniques are more cost effective than others for specific applications. The number of rehabilitation options considered should be selected based on experience and engineering judgment. Asset managers may be less adverse to consider new technologies and new materials when it can be demonstrated that applying rehabilitation methods with higher initial costs could result in lower life-cycle costs.

The illustrated technique is useful for asset managers when they are faced with the need to optimize resources (in this case, limited budgets). However, the successful application of this method depends significantly on the prediction of future applications. There are challenges in selecting discount rates and dealing with inflation. The selection of an appropriate discount rate and the method of dealing with inflation can have a significant influence on the outcome of the analysis. In addition to difficulties in the selection of discount and inflation rates, there are problems in quantifying disruption costs caused by rehabilitation work. These costs depend on many factors that include the projection of future circumstances of sewer location (i.e., sewers presently located in areas that are currently considered rural may be considered part of the urban sewer network 20 yr later). The sensitivity analysis of the outputs of the dynamic programming models to changes in input parameters including discount rate, inflation rate, maintenance costs, disruption costs, and expected service life is recommended so that asset managers can make decisions with greater confidence.

APPENDIX. REFERENCES

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