

Prioritizing Sewer Line Inspection with an Expert System

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1. Abstract

This paper describes the development of an expert system that prioritizes sewer inspection. The expert system also identifies potential risks and their consequences, provides an appropriate inspection test method, and alerts the user when more information is needed to make an accurate determination. Prioritizing sewer inspection identifies the critical reaches of the system, reduces the number of inspections, and as a result, reduces both emergency repair and preventative costs. The belief network logic of the expert system is based on information to be provided by the sewer utilities of ten medium-sized cities. The utilities will provide expert input on the probabilities of occurrence and relational dependencies associated with sewer line defects, condition assessment, and maintenance and rehabilitation procedures. This information helps assign the probability weights and relationships of the system's knowledge base. Feedback on prototype evaluations from the utilities will aid the validation process of the expert system development.

2. Introduction

Many cities are being serviced currently by non-inspected and deteriorating sewer infrastructure. Factors, such as weak materials, poor construction practices, and inadequate management, have made sewers less resilient to the natural aging process (Iseley, 1997). Examples of these factors are softened or absent mortar in brick lined sewers, improper trench compaction and materials, poor tunneling, infiltration and inflow, hydraulic overloads, and neglect. Deteriorating sewers leave communities vulnerable to unexpected catastrophic failures that disrupt not only sewer service but also above-ground activities. Failures are difficult to avoid if the cities are unaware of their pipes' condition.

The need to prioritize sewer inspection is a result of the uncertainty of the condition of buried infrastructure and the potential for costly and catastrophic system failures. By prioritizing sewer inspection, timely information can be obtained about the most critical reaches. Scheduling sewer inspection and the subsequent maintenance/rehabilitation process is a part of a utility's larger management plan.

The expert system described in this paper will not replace existing management plans, but enhance ongoing planning efforts. Many infrastructure management plans are focused on prioritizing rehabilitation. However, prioritizing rehabilitation requires a detailed inspection of a sewer system's lines. Therefore, prioritizing inspections is

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the first step in an infrastructure management plan when insufficient resources exist to inspect all sewers.

3. Previous Decision Support Tools for Sewer Evaluation

A number of decision support tools for analyzing transmission infrastructure currently exist. These tools can be classified as expert systems or optimization models. All tools require inspection information as necessary input and advise a rehabilitation plan as an output.

APOGEE is an expert system designed to diagnose structural defects in sewers and to plan sewer line rehabilitation (MacGilchrist, 1989 and Ortolano, 1990). This expert system gathers information on sewer line deterioration, such as structural defects and geotechnical conditions, and conditions of the surrounding environment such as sewer line dimensions and service history. APOGEE has autonomous modularized units that allow different users in the inspection, rehabilitation, and maintenance process to use the individual modules concurrently. APOGEE is hardwired into the utility database of Val de Marne County of France and therefore is used exclusively by this agency.

PIPES (Lim, 1997), also an agency specific tool, is an optimization model designed to prioritize repair, replacement and rehabilitation of the water distribution system for the Seattle Public Utility (SPU). This tool requires information from the SPU's GIS database, statistical analysis and subjective input to prioritize maintenance efforts based on three prioritization models, deterioration, vulnerability, or criticality. A model execution prioritizes maintenance efforts based on one of the three prioritization models. Both the APOGEE expert system and the PIPES optimization model are constructed for and used exclusively with an existing database system.

The remaining two tools are optimization models. Although these models are not database specific, each model has been used to create a rehabilitation plan for one utility. Both models require a full inspection of an existing system to report a rehabilitation plan. The Multi-Attribute REhabilitation of Sewer System (MARESS) model produces a rehabilitation plan by optimizing numerous objectives such as minimize maintenance costs, minimize disruptive costs, maximize structural conditions, and maximize hydraulic conditions. The MARESS model is adaptable for separate or combined sewers and includes rehabilitation technologies (Reyna, 1993).

The Burgess model creates a long-term rehabilitation strategy using a probabilistic Markov state matrix process (Burgess, 1988). The model runs various rehabilitation strategies through a temporal model that incorporates both predicted sewer line rehabilitation and deterioration. Each iterative run displays an optimal strategy based on system input costs and failure related imposition costs. The Burgess model provides a long-term planning strategy and allows for cost updates.

4. Prototype System

Previous prioritization efforts have focused most closely on rehabilitation rather than inspection. An example of such efforts can be found in the Water Research Center Sewer Rehabilitation Manual, a standard for the UK that has been used worldwide (Hurley, 1994 and USDHUD, 1988). The approach includes four phases: planning the investigations, assessing structural condition and hydraulic performance, developing the drainage area plan, and implementing the plan

(WRc, 1986). The first phase (planning investigations) involves upgrading sewer records, assessing areas of known problem and identifying critical sewers. The expert system described here mimics and expands upon this first phase.

A prototype version of the expert system is being created that catalogues information for both inspected and non-inspected sewer lines and prioritizes the inspection of sewer lines. In addition, the expert system identifies potential risks and their consequences, provides an appropriate inspection test method, and alerts the user if more information is needed to make an accurate determination. The tool has three components but executes as one program. Figure 1 shows these components.

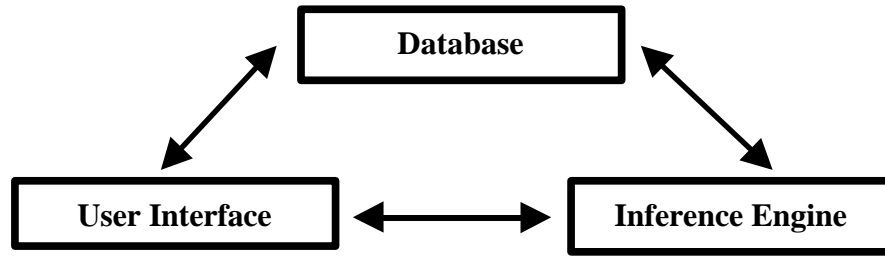


Figure 1. Expert system components

The first component is a database that contains information about each sewer line to be prioritized. The database can either be an adaptation of an existing database or created by the user. The second component of the program, the user interface, contains visual prompts for the user to enter information, provides help information on system program use and program assumptions, and provides access to the database. The third component, the inference engine calculates the appropriate actions to be taken based on belief network logic. In symphony, the three components produce information that enables the user to catalogue sewer line information, prioritize inspections, and select an appropriate maintenance or rehabilitation procedure.

5. Expert System

A Bayesian belief network is used as the expert system inference engine. Belief networks differ from rule based system because they allow the propagation of uncertainties that may be associated either with the appropriateness of a rule or the values of a particular variable. Belief network logic includes both rules (such as If $A \cap B$ and $C \cap D$, then E) and the distribution of joint probabilities. Belief network logic can be described graphically by a series of nodes and arcs. The nodes of the graph represent variables. Variables can take on one or more values from a discrete group of states. An arc between variables represents a relationship or dependency between the two variables, which is determined by the conditional probability between the variables (Gryzymala-Busse, 1991 and Shafer, 1996). The tail of the arc indicates the cause of the effect on the variable at the head of the arc. The “from” node is the cause of the effect of the “to” node.

In Figure 2, *Pipe Material*, *Ambient Temperatures* and *Corrosion* are nodes. The *Pipe Material* and *Ambient Temperature* nodes are the causes of the effect node, *Corrosion*. The *Corrosion* node has three states associated with it, High, Moderate, and Low, the *Ambient Temperature* node has two states, Above 50°

and Below 50°, and the *Pipe Material* node has three states, Concrete, Brick, and Other.

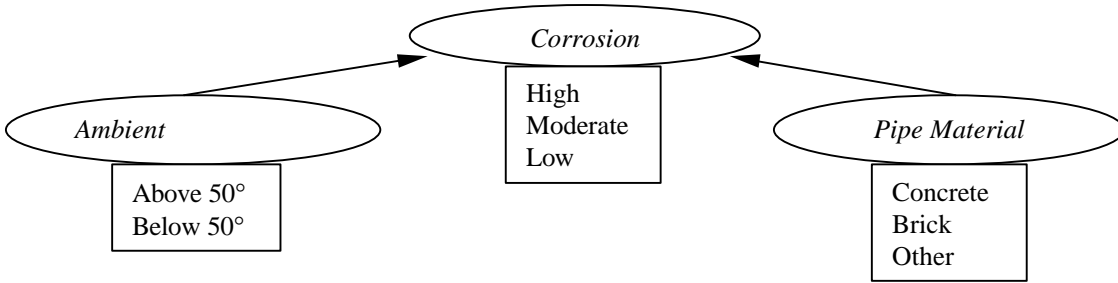


Figure 2. Belief Network Node Example

For each combination of causal variable states there is a corresponding effect variable state described by the strength of the dependency. The strength of the dependency (also known as the uncertainty or confidence) is determined by the conditional probability between the variables. For example, event A is the occurrence of “high” *Corrosion*, event B is “concrete” *Pipe Material*, and event C is “above 50°” *Ambient Temperature*. A sewer infrastructure expert may believe that the probability of event A occurring given that event B and event C occurred is 80% or $P(A|B, C) = 0.8$. The degree to which event A occurs given event B and event C occur is a dependency strength based on the conditional probability of 0.80.

Bayesian belief networks, or causal networks, are probabilistic processes that determine effects or outcomes of an associated uncertainty. The dependency strength at each node is a representation of the uncertainty at that node. Within the network, each effect node (with the exception of the final node) is a causal node as the relationships propagates through the network. The dependency strength or uncertainty, also, is propagated through the belief network.

The *Corrosion* node is an effect node in Figure 2. However, in the Figure 3, the *Corrosion* node is now a causal node (along with the *Joint Defects* node) for the effect node *Structural Defect Formation*. The uncertainty associated with the *Corrosion* and *Joint Defects* nodes will now be propagated through the system based on the relational dependency between these three variables. Therefore, the uncertainty is propagated through the system of conditional relationships as each causal node defines the uncertainty of the next layer by calculating the conditional probabilities.

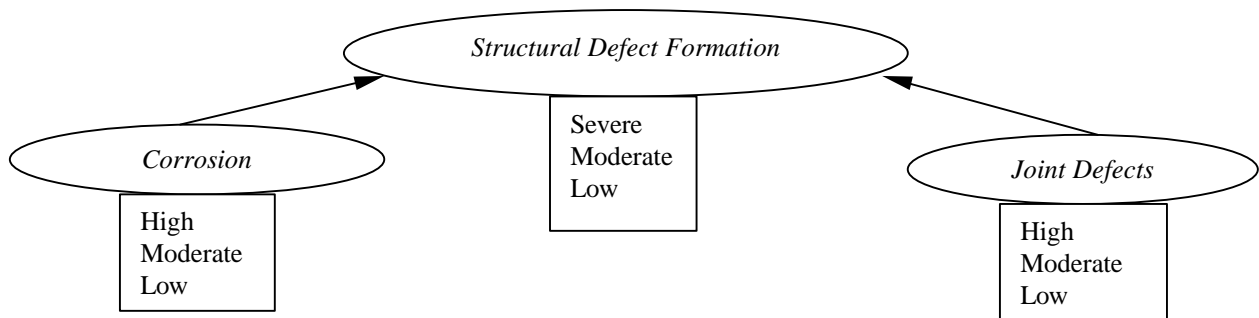


Figure 3. Belief Network Uncertainty Propagation Example

A formal description of the propagation of uncertainty is described as follows (Heckerman, 1995): Let Y be a vector which represent the set of nodes ($y_1, y_2, y_3, \dots, y_i$) influencing a specific node X . Let the states of the variable at node X be defined as X^k . The confidence that X assumes a specific value k is defined as:

$$p(X^k) = \sum_{i=1}^n p(X^k | y_i^j) p(y_i^j)$$

where:

$p(X^k)$ = confidence associated with the node X assuming the state k

$p(X^k | y_j^i)$ = confidence that node X assumes the state k when causal node i assumes a value of j , and

$p(y_i^j)$ = confidence that causal node has assumed state j

6. Knowledge Acquisition

The information to be contained in the belief network is gathered by a series of interviews from sewer managers in medium-sized cities and experts in Brown & Caldwell. Cities currently identified to participate in the interview process include Eau Claire WI; Seattle, WA; Portland, OR; Des Moines, IO; Boston, MA; Cleveland, OH; King Co, WA; and Phoenix, AZ.

Knowledge acquisition is the iterative process of obtaining knowledge from experts, incorporating the knowledge into the expert system and testing knowledge, logic and usability of the prototype. The knowledge acquisition process includes domain familiarization, development and distribution of questionnaires, and conducting formal and informal interviews (McGraw, 1989). A knowledge acquisition database is created to organize and classify comments, conditional relationships, and domain definitions. The database is used to build the belief network logic, compare expert information, and develop program assumptions and on-line help. The database also serves as an easily accessible reference center for all tool developers and expert participants.

7. System Logic

The first step in creating the system logic is to define the repair/rehabilitation requirements so that the inspection prioritization can lead the user to the most critical areas of the sewer system. The requirements are categorized into 7 levels:

Level 1 – No Immediate problem – re-inspect in a specified number of years.

Level 2 – Problems need further definition associated with conditions.

Level 3 – Perform routine/planned maintenance.

Level 4 – Stabilization (slow deterioration/corrosion protection).

Level 5 – Structural Rehabilitation.

Level 6 – Complete Replacement.

Level 7 – Immediate Attention.

The factors of sewer line deterioration that define the repair/rehabilitation requirements are developed from the questionnaires and interviews of the knowledge acquisition. The relationships between the sewer line deterioration factors are the basis for the belief network and the system logic. The system logic is the belief network with domain specific variables and variable states.

The top level of system logic is an inspection prioritization based on one of the seven repair/requirements. The second level of system logic represents the effect the deterioration factors on the Probability of Failure and on the Consequence of Failure.

Tables 1 and 2 are a simplification of the prototype system logic. Table 1 is a schematic for the cause and effect relationships that describe the Probability of Failure rating. Similarly, Table 2 shows the relationships that describe the Consequence of Failure rating. The bulleted/italicized items are pieces of information the user would enter into the expert system and represent the bottom level of the system logic. The bolded items represent intermediate states of logic that contain the conditional probability or uncertainty that has propagated up through the network.

8. Future Work

The work to date for this project includes the development of the initial questionnaire, a preliminary schema for the system logic, and a prototype containing the three program components (database, user interface, and inference engine). Future work will include enhancing the knowledge base, developing a more inclusive schema, and improving the program with subsequent prototypes. In addition, future work includes performing validation testing, sensitivity analysis, and usability testing. Validation will be performed by field testing prototypes and comparing the inspection prioritization with the rankings from several. Differences in the ranking by the expert system and the experts will be traced through the logic of the belief network and a determination will be made as to the significance of the differences and what changes need to be made to the tool as a result.

A sensitivity analysis will be performed on the variables to determine their influence on the final ranking decision. The greater the influence of a variable on the final prioritization ranking, the more crucial it is that the input provided by the user is accurate. The sensitivity analysis, therefore will help to determine what sewer line information can be entered as “unknown” by the user for a valid system application (Coupe, 1997).

Usability issues involve the user’s understanding of interface prompts, accessibility of the database, navigation through the data entry process, and the effectiveness of on-line help. Usability of the expert system will be monitored as the prototypes are demonstrated in the validation process. Usability testing will be performed by recording comments during and after the prototype demonstration sessions and by observing video taped demonstration sessions.

Table 1. Probability of Failure Relationships (Cox, 1998)

Structural Defect Formation				Operational Effects			Catastrophic Occurrences	
Corrosion	Joints	Infiltration	Inspection Defects	Operational Defects	Operational Environment	Flooding	Historical Crisis	Earthquake Risk
<ul style="list-style-type: none"> ◦ Ambient air temp ◦ Water strength ◦ Material ◦ Age ◦ Corrosion soil type ◦ Groundwater 	<ul style="list-style-type: none"> ◦ Expansive soils ◦ Construction practices 	<ul style="list-style-type: none"> ◦ Infiltration Soil Type ◦ Groundwater levels ◦ Material ◦ Age 	<ul style="list-style-type: none"> ◦ Mortar defects ◦ Brick defects ◦ Infiltration ◦ Corrosion ◦ Joint conditions ◦ Cracks ◦ Fractures 	<ul style="list-style-type: none"> ◦ Root intrusion ◦ Debris ◦ Scale buildup ◦ Grease 	<ul style="list-style-type: none"> ◦ Trees above line ◦ Food processing plant ◦ Restaurant cluster 	<ul style="list-style-type: none"> ◦ Basement ◦ Street 	<ul style="list-style-type: none"> ◦ Landslide occurrence ◦ Collapse occurrence 	<ul style="list-style-type: none"> ◦ Earthquake risk ◦ Liquefaction potential

Table 2. Consequence of Failure Relationships (Cox, 1998)

Reconstruction Cost Impacts			Service Impacts		Surface Impacts			Environmental Impacts	
Surface and Soil Costs	Trench Costs	Old Pipe Costs	Redundancy	Hydraulic Capacity	Access	Traffic	Location	Receiving Body Water	Sensitive Areas Cleanup
<ul style="list-style-type: none"> ◦ Location ◦ Soil stability conditions 	<ul style="list-style-type: none"> ◦ Depth of invert burial ◦ Groundwater table 	<ul style="list-style-type: none"> ◦ Material ◦ Pipe diameter 							

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