Fall 1994

Development of a Knowledge-Based System for Wastewater Pipeline Rehabilitation

David Allen Reaves
Old Dominion University

DEVELOPMENT OF A KNOWLEDGE-BASED SYSTEM

FOR WASTEWATER PIPELINE REHABILITATION

by

David Allen Reaves
B.S. December 1992, Old Dominion University

A Thesis submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE

ENGINEERING MANAGEMENT

OLD DOMINION UNIVERSITY
December, 1994

Approved by:

Derya A. Jacobs (Director)

Billie M. Reed

Han A. Bao

ABSTRACT

DEVELOPMENT OF A KNOWLEDGE-BASED SYSTEM FOR WASTEWATER PIPELINE REHABILITATION

David Allen Reaves
Old Dominion University, 1994
Director: Dr. Derya A. Jacobs

The purpose of this thesis is to study and develop a knowledge-based system to make decisions for the rehabilitation of wastewater pipelines. Development includes justification for the use of an expert system, data acquisition from knowledge experts, program model development, model testing, implementation and future considerations including expansion. The model is developed and implemented using an expert system shell called XI-Plus®.

This knowledge-based system is designed specifically for the Navy Public Works Center Utilities Department at Norfolk Naval Base in Norfolk, Virginia for making decisions for the rehabilitation of the 50-year-old wastewater collection system. Recent sewer collapses and a mandate by the Hampton Roads Sanitation District to reduce inflow and infiltration during wet weather periods has increased the need to expedite sewer repairs throughout the base.

ACKNOWLEDGEMENTS

There are so many people that I want to thank for their help. They include my advisors, Derya A. Jacobs, Billie M. Reed and Han A. Bao, my wife, Deborah M. Reaves, my co-workers, Paul M. Atkinson and Fred Dufault, my mother, Betsy P. Little, my sister, Amanda Paige Little, my brother-in-law, Ronald E. Menold II, my mother-in-law, Deanna Menold and my sister-in-law Cheryl Weaver. Your insight and experience have been invaluable to the completion of this thesis. **God Bless each and every one of you.**

To my son Tyler Matthew...

there is nothing more important than a good education.

TABLE OF CONTENTS

LIST OF TABLES vi

LIST OF FIGURES vii

Chapter

1. INTRODUCTION 1

Background 1
Problem Statement 2
Research Objective 4

2. LITERATURE REVIEW 5

Introduction 5
Computer Models 6

Optimization of Design Layout for Sewer 6
Computer Maintenance Scheduling in San Francisco . 7
City of Seattle Rehabilitation Program 7
City of Houston Sewer Rehabilitation Program 8
South Austin Relief Main Rehabilitation 8
Topeka Uses Computers for Sewer Rehabilitation . . . 9

Existing Models Versus Thesis Objective 9

3. RESEARCH METHODOLOGY 11

4. CONCEPTUALIZATION AND SYSTEM ANALYSIS 13

Conceptual Design 13
Development Strategy 15
Sources of Knowledge 15
Selection of Computing Resources 16

5. SYSTEM DEVELOPMENT 17

Definition of Potential Recommendations 17
User Provided Information 22
Development of Knowledge-Based Rules 26

Virginia Department of Health Regulations 28
Material Considerations 30
Surface Type Considerations 31
Location Considerations 32
Depth Considerations 32
Pipe Condition 33
Infiltration Percentage 34
Scoring Method to Select Rehabilitation Alternative 35
Caveats to Final Repair Method 39

Cross-Connection Recommendations 40
Break-in Service Connection Recommendations 40
Protruding Connection Recommendations . . 40
Abandoned Connection Recommendations . . 41
Change in Pipe Size Recommendation 41
Corroded Pipe Recommendations 42
Root Growth Recommendations 42
Mineral Deposit Recommendations 43

6. EVALUATION AND VALIDATION OF KNOWLEDGE-BASE 44

7. DISCUSSION AND CONCLUSIONS 47

BIBLIOGRAPHY 49

APPENDIXES

A. Definition of Terminology 51

B. Rules for Knowledge-Based System 56

C. User Input Forms 80

LIST OF TABLES

Table 1. Pipe Segment Length & Roughness for Material Types 31

Table 2. Surface Type Ratings 31

Table 3. Political Sensitivity for Different Locations 32

Table 4. Trench Cost for Different Depths 33

Table 5. Pipe Condition for Different Critical Defect Percentages 34

Table 6. Infiltration Condition for Different Infiltration Percentages . . . 35

Table 7. Repair Scores for Different Levels of Trench Cost 36

Table 8. Repair Scores for Different Levels of Surface Cost 36

Table 9. Repair Scores for Different Levels of Political Sensitivity 37

Table 10. Repair Scores for Different Levels of Infiltration Condition . . . 37

LIST OF FIGURES

Figure 1. Slip-lining Method 20

Figure 2. Cured-in-Place Method 21

CHAPTER 1

INTRODUCTION

Background

Norfolk Naval Base at Sewells Point, Virginia is the world's largest Naval facility. Most of the base infrastructure was built in the early 1940's during World War II. Fifty years later, much work is needed to repair the different utility systems. In particular, extensive corrective measures are needed throughout the base to bring the wastewater collection system into compliance with current standards.

The sanitary sewer system services 50,000 people per day and is comprised of 40 miles of pipeline from four-to-36 inches in diameter. Pipe materials include clay, concrete, iron and polyvinyl chloride. The collection system services all areas of the base, including home-ported ships of the fleet, the air station and Navy housing communities.

There are two main reasons for making immediate repairs to the system: 1) increased incidents of pipeline failures and 2) a requirement by the Hampton Roads Sanitation District (HRSD) to reduce inflow and infiltration during wet weather periods. Increased pipeline failures keep maintenance and engineering personnel in a reactive mode versus a proactive mode. These failures are costly and interfere with the day to day operations of the naval base. HRSD is requiring the Public Works Center (PWC) Utilities Department to reduce inflow and infiltration so that the wastewater treatment plant is not inundated during wet weather periods. Additionally, the sewer system surcharges to near surface level during high intensity storms. Exceeding system capacity could create environmental hazards in several areas due to sewage backups.

PWC Utilities is responsible for maintaining the wastewater collection system via two divisions: Reliability Engineering Division and Distribution Division. The Reliability Engineering Division is responsible for major maintenance work done on the system. This includes all work over 75,000 dollars. The Distribution Division is responsible for the day-to-day running of the system, including preventive maintenance and small repairs as needed to ensure reliable service to all customers.

Problem Statement

PWC Utilities is evaluating large portions of the wastewater collection system for the purpose of gaining information needed to make cost-effective repairs to the system. This evaluation requires large amounts of data to be assessed by PWC Utilities personnel. Currently, the data is assessed manually. This process is time consuming and lengthy given current staffing. Only 30%

of the base has been studied to date and considerable work is required in the next two-to-three years.

The evaluation process analyzes data associated with pipe material, surface condition, location, slope, velocity, capacity, infiltration condition and pipe condition. This combination of information leads to numerous repair alternatives. In general, these repairs include replacement, spot repair, slip-line, cured-in-place and pipe insertion. Often times, a spot repair is needed prior to using slip-line or cured-in-place. Additional considerations include the condition of service laterals at the connection to sewer mains. With more than 3,000 pipeline sections in the system, these evaluations are overwhelming.

Affecting repairs in a timely fashion is essential. There have been several sewer line collapses in the last five years. In particular, a parking lot in front of Pier 2 collapsed during the Desert Storm War. This collapse effected Naval operations and tremendous costs were incurred in quickly and effectively repairing the damaged pipeline. Under the current administration, government cutbacks have inhibited the PWC Utility Department's ability to hire the additional staff needed to assess the wastewater collection system and make the appropriate repairs. This, in combination with an aging system, indicates the need for an investigation into a more efficient way to assess large quantities of data.

Research Objective

The research objective is to assess the existing rehabilitation decision process for individual pipeline sections and to develop a computerized model to support the PWC Utility Department in making these decisions. Objectives of the system include:

- bridging the gap of time between evaluation and rehabilitation
- developing a more consistent repair selection
- standardizing the decision-making process

Meeting these objectives should assure compliance with local requirements while improving the integrity of the sewer collection system.

CHAPTER 2

LITERATURE REVIEW

Introduction

Most wastewater collection systems throughout the United States have reached or exceeded their design life. This has created an information explosion within the industry over the last ten years. Computer models are now used in assorted ways to assist in the organization of information for the rehabilitation of sanitary sewer systems. The key difficulty in dealing with any system is survey data and physical data.

Survey data includes the horizontal and vertical control associated with a pipeline section and is used to ensure that certain basic parameters such as slope and capacity can be determined. Physical data includes an internal television inspection of each pipeline section and an inspection of surrounding surface conditions.

Computers assist the user in the assimilation of such data and allow flexibility in how the data is used and reported. Below are some of the ways that microcomputers are being used to assist in maintaining a sewer system:

- optimization of layout
- analysis of flow systems
- assistance in evaluation of contractor performance
- compilation of maintenance records to determine repair priority
- collection and recordation of defects for pipeline sections
- creation of databases for television logs
- formulation of databases to assimilate survey results
- selection of possible rehabilitation methods

Computer Models

Computer models are essential to successfully maintaining a sanitary sewer system. Models found in the research cover design and maintenance aspects of sewer systems. Areas of design using computer models include sewer system layout optimization and hydraulic capacity analysis. Computer models for maintenance track, determine and schedule the maintenance and rehabilitation of line sections within a flow area. The use of computers allows continual update of data and consistent improvement in sewer system performance.

Optimization of Design Layout for Sewer

Heuristic algorithms are used to select the pipe diameters, slopes and invert elevations of a given horizontal layout which yield the least costly design considering material, excavation, installation and manhole costs. Several constraints can be used to ensure a layout that is feasible. The basis of this type of work is optimization using model simulation techniques [Tekeli, 1986].

Computer Maintenance Scheduling in San Francisco

The computerized sewer maintenance scheduling system has four basic elements: *database*, *criteria*, *analysis program* and *scheduler*. All information regarding physical attributes are stored in the *database* and include previous and future data. The *criteria*, which consists of rules that dictate the operation of the decision-making system and provide a measure of effectiveness, are a set of goals and objectives translated into a logical form that are used by the scheduler. The *criteria* is controlled by the agency manager and maintenance superintendent. The *analysis program* provides reports on performance The *scheduler* prepares and delivers a cleaning schedule to the maintenance superintendent. Once scheduled lines are cleaned, the database is updated and an iterative process begins throughout the collection system [Schaaf, 1985].

City of Seattle Rehabilitation Program

The City of Seattle, Washington, collected maintenance reports and inspection forms for many years prior to 1988. Although the city had an organized system, the data needed to be condensed into something more manageable. Hansen Software, Inc. was hired to inventory the 1,550 miles of sanitary sewer and 36,000 manholes. This included assimilation of existing data and newly collected field data. The result of this effort was a database one-tenth its original size for all maintenance and inspection reports. An expert-based model was also created to assist in the selection of rehabilitation alternatives based on comparative cost of construction versus the cost of transportation and treatment. Additionally, Hansen Software, Inc. created a program to schedule preventative maintenance based on information found during daily inspections [Clendaniel, 1989].

City of Houston Sewer Rehabilitation Program

The City of Houston, Texas, underwent an unparalleled effort from 1989 to 1991 to inspect, evaluate and select rehabilitation methods for its 4,500 miles of sanitary sewer. Hansen Software, Inc. was selected to computerize this effort. Work included the collection of physical data and television inspection reports. All data was downloaded into proprietary database software developed by Hansen Software, Inc. This database was used to supply information to a rule-based expert system designed to suggest rehabilitation alternatives. The other key element to this project was the use of a structured query language to assist in the generation of new reports to help evaluate contractor work and work in performance. This created a consistent and time saving method of communication throughout the course of projects [Gregory, 1990].

South Austin Relief Main Rehabilitation

South Austin, Texas used microcomputers to analyze 6.4 miles of 24-inch through 54-inch diameter gravity wastewater interceptor that serves approximately 60,500 people. Computer models determined current flow conditions, developed population projections and determined the appropriate pipe characteristics to meet future needs. The use of computers in this instance enabled a timely and accurate assessment of rehabilitation needs for the gravity line [Capone, 1988].

Topeka Uses Computers for Sewer Rehabilitation

Topeka is the oldest city in Kansas and has 660 miles of sewer that serves 123,000 people. Microcomputers are used to create a sanitary sewer management system which includes databases for both manholes and pipeline sections. User menus make the interface between machine and human more simplistic and allow for easy updating of the databases. An interface between the system database and the maintenance management program makes comparison of control data and inspection data for rehabilitation determination easier. Hydraulic models were created to model the system and determine the impact of wet-weather flow. Essentially, Topeka's sanitary sewer management system enhanced the knowledge of system loadings and hydraulic capacities and created an environment for better decision-making [Gray, 1988].

Existing Models Versus Thesis Objective

Existing models focus on a variety of important topics from maintenance scheduling to rehabilitation selection. Models found in the literature review use the basic principles and concepts of engineering practice for sanitary sewer. The existing models focus on municipalities with systems that are used to service urban-type areas.

Although these areas have unique circumstances, the impact of a particular rehabilitation method on the daily activities of a city cannot compare to the possible impact on a naval base. Hence, the most cost effective repair is not always the best repair. That is the fundamental difference in this model.

Political sensitivity and the naval base mission have a high impact on the decision-making process for rehabilitation. The actual decision for a rehabilitation method is swayed more by political concerns then conventional engineering wisdom.

Secondly, most sewer systems are found along street centerlines. The naval base has sewer lines anywhere from an Admiral's back yard to the end of a pier servicing a battle ship. Therefore, costs vary widely based on the surface condition. This unique situation must be accounted for in the model.

Thirdly, meeting the needed capacity is absolutely necessary to the service of the base. Therefore, capacity is always checked to make sure the needs of the military are met. This is especially important during times of war when ships are frequently in and out of port.

Chapter 3

RESEARCH METHODOLOGY

Alternative solutions were evaluated to determine the appropriate approach for meeting the needs of the PWC Utility Department. These evaluations explored the effectiveness of various computer-based techniques and their feasibilities in addressing and meeting the stated objectives.

The stated objectives were clearly defined through a needs assessment that identified areas of concern. Currently, more engineering help is needed to review data and make rehabilitation decisions. Such personnel require extensive, time-consuming training to acquire the unique decision making process skills for the naval base and acquisition of more staff is not presently possible due to federal hiring restrictions. Instead, resources can be used to create a computer-aided approach to decision making.

Conventional software is incapable of handling the heuristics involved in making repair decisions as the conditions change throughout the naval base. The second most important factor that precludes the use of conventional software is the inherent inflexibility in making changes to the original system.

This is extremely important in a world of fast-changing technology. A knowledge-based approach provides the flexibility and use of heuristics needed to communicate rehabilitation techniques via computer systems. This approach is appropriate to this situation for the following reasons:

- the task is decomposable into many different segments
- the task is developed by human experts
- the problem is of a manageable size
- the concept has practical value for daily functions

In addition, certain requirements are needed to ensure the success of an expert system approach. They include:

- experts who cooperate
- experts who communicate their problem solving methods
- multiple experts who agree on solutions
- tasks that are understood and clearly defined
- incorrect results are tolerated
- data and test cases are available

The decision process for sanitary sewer requires an intuitive knowledge of the many heuristics involved with wastewater flow and defect analysis. There are four experts at the Navy Public Works Center Utilities Department with the appropriate communication skills to effectively describe the problem solving methods. Three of the experts are Civil Engineers and one is a Civil Engineering Technician. The four experts have a combined experience of over 48 years, with over 24 years of utilities experience at the naval base. Since this group of experts work well together, repair decisions will reflect the unique situation appropriate to a naval base.

CHAPTER 4

CONCEPTUALIZATION AND SYSTEM ANALYSIS

Project conceptualization and system analysis of a knowledge-based system is divided into four components as follows:

- conceptual design and plan
- development strategy
- knowledge sources
- computing resources

These components are essential to the eventual prototyping and full development of the knowledge-based system. The groundwork for development is established in the conceptual design phase as discussed below.

Conceptual Design

The conceptual design forms the basic ideas comprising the knowledge-based system. This includes defining the different repair options that result from a consultation with the system and the parameters that affect this outcome.

Repair options include *replacement*, *spot repair*, *slip-line*, *cured-in-place*, *pipe bursting*, *slip-line with spot repair* and *cured-in-place with spot repair*. *Replacement* is generally used when there is a high percentage of critical defects, the capacity is inadequate or the pipe slope is reverse grade. *Spot repair* is generally reserved for those line sections that have a small percentage of overall defects. *Slip-line* is a process whereby a new pipe is inserted inside the existing pipe. This method requires an excavation pit to insert the new pipe. Slip-lining effectively reduces the diameter of the line section by one pipe size. This is frequently offset by the increased flow due to a reduced friction coefficient. *Cured-in-place* is a trenchless repair method which uses a resin-impregnated liner that forms to the inside of the existing pipe. This method increases flow capacity without disruption to the surrounding surface. *Pipe bursting* is mainly used to increase the pipe size with minimal disturbance to the surrounding area. A bursting machine is used to expand the pipe in the ground. A new line with increased sized is pulled through to fill the resultant cavity. Excavation pits are needed at each end of the work area. Spot repairs are often necessary before slip-lining or cured-in-place are performed. Normally, the extent of these spot repairs is limited when using these two methods.

Knowledge of repairs is equated to an initial scoring system used to rate the different repair methods. The initial scores are evaluated on four parameters: trench cost, surface cost, political sensitivity and percentage of inflow and infiltration defects. The selected repair method is then evaluated with the percentage of critical defects to determine the final repair method.

Development Strategy

The research objective is to develop a system for the PWC Utility Department that effectively interfaces with personnel relatively inexperienced in decision making processes of rehabilitation selection. The PWC Utility Department has the skills and necessary resources available to develop this expert system. The critical factor involved in the design of this knowledge-based system is the presentation of data acquisition and final recommendations using forms in XI-Plus®.

Sources of Knowledge

Documented and undocumented resources are vital to the development of this knowledge-based system. Manuals from the Virginia Department of Health (VDH) and the Department of Environmental Quality (DEQ) on wastewater standards and the Handbook for Civil Engineers provide information needed to ensure that minimum requirements are met and proper techniques are used in making each repair decision. Closed circuit television video is used to document the defects in each pipe section. These defects are tabulated by type and input directly by the user. A database is used to organize the horizontal and vertical information, including physical characteristics, associated with each line section. Undocumented knowledge is captured through interviews with the engineering staff at the PWC Utility Department. Essentially, interviews are used to develop the heuristics involved with wastewater rehabilitation at Norfolk Naval Base.

Selection of Computing Resources

This knowledge-based system is created using a shell called XI-Plus®. All work is done on a 486-33 Mhz computer under the Disk Operating System (DOS). XI-Plus® is an appropriate shell since it is rule-based and employs forward chaining. XI-Plus® is user friendly and offers great flexibility in data acquisition, programming and reporting.

CHAPTER 5

SYSTEM DEVELOPMENT

Development of a knowledge-based system involves several steps. The first step is to define the potential solutions/recommendations. The second step is to determine all possible user input needed to arrive at those recommendations. The third step is to determine all applicable rules, heuristics and facts needed to apply the input toward a reasonable recommendation.

Information collected is a result of interviews conducted with the experts. These interviews precipitated additional discussions which continually refined the rule-based system. Group interaction is essential to ensure group conformity for the basis of rules and the selection of rehabilitation methods.

Definition of Potential Recommendations

There are seven potential rehabilitation methods that should be considered for this knowledge based system: *replacement*, *spot repair*, *slip-line*, *cured-in-place*, *pipe bursting*, *spot repair with slip-line* and *spot repair with cured-in-place.*

Replacement involves construction of a new pipe along the same alignment as the existing pipe and is generally performed when the existing pipe has severe structural or alignment defects, inadequate capacity, or chronic maintenance problems due to poor slope. Pipe can be installed either in the same trench with the existing pipe being removed, or in a parallel trench with the existing pipe abandoned in place. Replacement pipe material is polyvinyl chloride (PVC) with a standard dimension ratio of 18. Ductile iron pipe is used when temperatures may exceed 140 degrees or the depth to top of pipe is over 12 feet.

Slip-line is a method for inserting a new pipe within an existing pipe and is used in cases where high inflow and infiltration defects exist and the line section is in otherwise good condition. The pipe used is a fusion-bonded, high density polyethylene (HDPE) that is inserted through access pits. The pipe is inserted by pulling it through the existing pipe as shown in Figure 1. In some cases, pushing techniques are used to install the liner. *Slip-line* requires adequate clearance between the outside of the liner pipe and the smallest inside dimension of the existing pipe. The result is a renovated pipe that has a step in the invert at the beginning and end of each liner. After the HDPE is inserted, the annular space is completely filled with mortar or other suitable filler to create a structural bond with the old pipe to prevent water from entering the annular space. The filling material is inserted using pressure grouting techniques.

Cured-in-place is a trenchless repair method used to repair lines with high inflow and infiltration defects and involves the insertion of a flexible, resin-impregnated synthetic fabric liner into a sewer pipe. The liner is custom fabricated to match the inside dimensions and length of each pipe section to be lined. The liner is expanded against the pipe wall by introducing water or air into it. After the liner is in place, it is cured using hot water, steam or ultraviolet light as shown in Figure 2. The cured liner has structural strength, mends pipeline structural defects, spans short lengths where the sewer pipe is missing and provides a leak-free pipe within the existing pipe. Although the diameter size is slightly reduced, increased capacity is usually created due to a smaller coefficient of friction.

Pipe bursting is generally used to increase the size of lines with a capacity that is less than adequate and where replacement is not a preferable alternative due to political considerations. This method requires access pits at either end of the line section. A triangular head is pulled through the existing pipeline to create a larger void than the original pipe. The new HDPE line is pulled in behind the pipe bursting machine allowing the newly created void to be immediately filled. The pipe is fused together in a manner similar to *slip-line* as it is pulled in place.

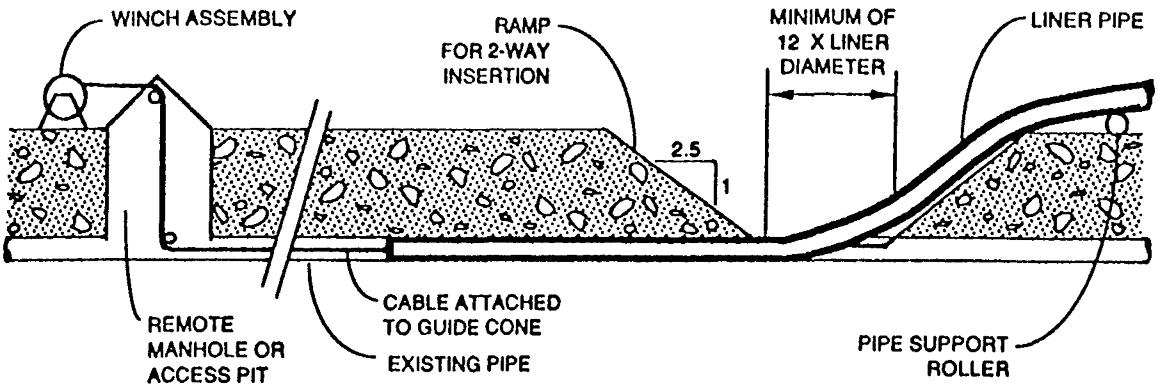

Figure 1. Slip-lining Method

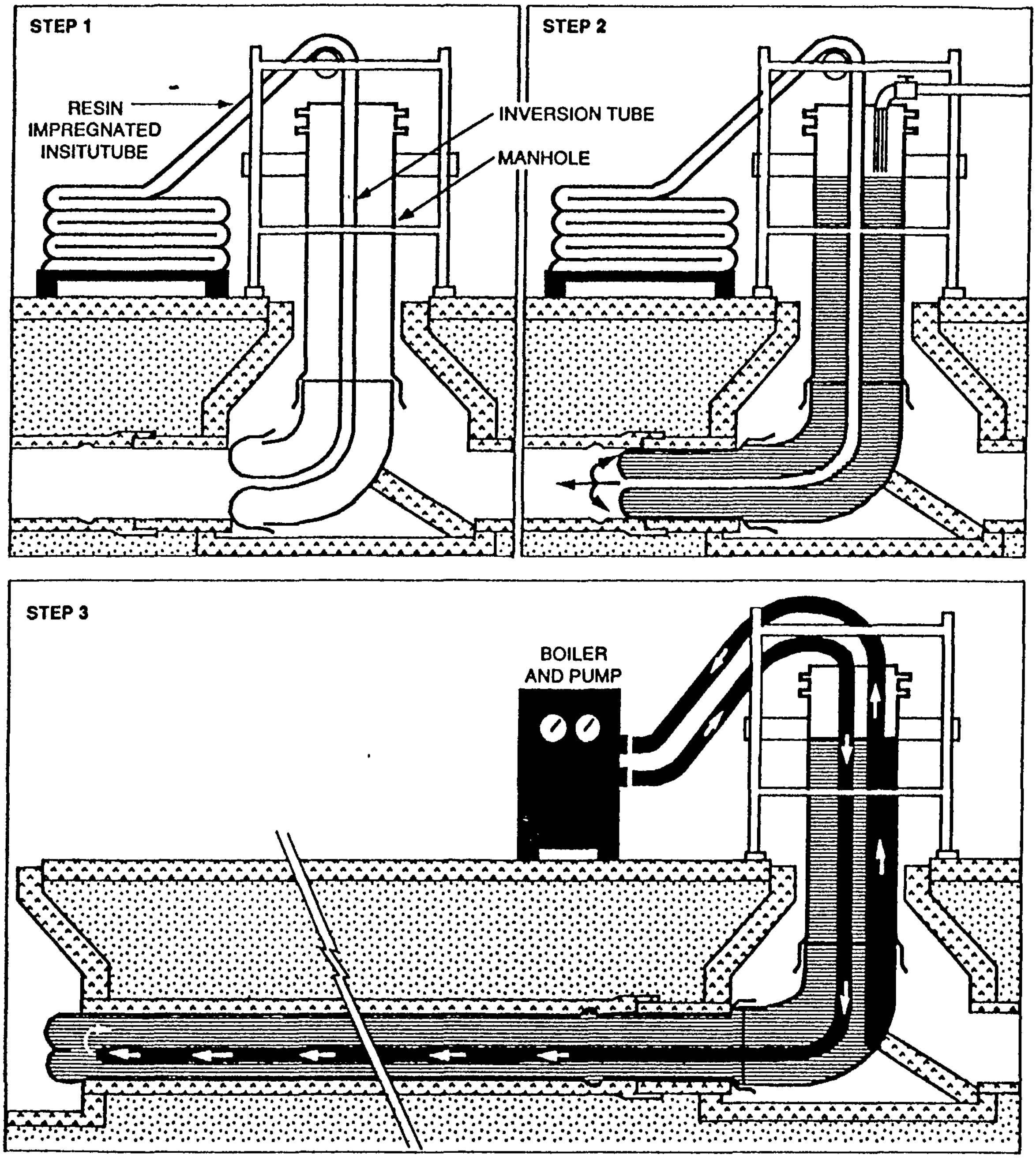

Figure 2. Cured-in-Place Method

Spot repair with slip-line is used in cases where *slip-line* is the preferred alternative but there are some critical defects that inhibit the liner from passing. The critical defects are first repaired via spot repair then the entire line section is slip-lined. The same scenario holds true for *spot repair with cured-in-place*.

User Provided Information

There are ten main categories for user input. They include defects, pipe material, pipe diameter, pipe length, upstream manhole invert out, downstream manhole invert in, average pipe depth, pipe location, surface condition and capacity required to meet service needs.

Defects are categorized as: infiltration, capacity or critical defects. *Infiltration defects* include cracked joints, offset joints, open joints, leaking joints, mineral deposits, root growth, circular cracks, longitudinal cracks, multiple cracks, missing pieces, leaking service connections, abandoned service connections, break-in service connections, protruding service connections and holes in the pipe. The four service connections are included as *infiltration defects* since they frequently contribute to infiltration in the annular space between the lateral and host pipe. *Capacity defects* include changes in pipe size and corroded pipe. A *change in pipe size* most often indicates a smaller diameter pipe at a particular point along the pipe section. The length of most pipe size changes is limited to a few pipe sections. *Corroded pipe* is found in ductile iron (DI) and cast iron (CI) pipes. The corrosion is a result of hydrogen sulfide gases combining with the cement lining found in most iron pipes. This creates a very rough surface inside the pipe wall and reduces the effective velocity which in turn affects the available capacity of that line section. *Critical defects* include severe dips in the line, horizontal mis-alignments, blockages, deformed pipe and crushed pipe. *Severe dips* are those pipe sections which sink (belly) greater than one-fourth the diameter of the pipe. These bellied sections of pipe encourage the accumulation of material or blockages within the pipe section thus inhibiting the flow. *Deformed pipes* are normally the result of PVC pipe that has been exposed to temperatures in excess of 140 degrees Fahrenheit. These excessive temperatures actually melt PVC pipe like a wax candle. Such high temperatures in sewer is credited to defective cooling wells for steam condensate that drain into the sanitary sewer. The proper solution is to use DI pipe and fix the cooling well. DI pipe ensures that a failed cooling well will not harm the sewer system.

Pipe material is directly correlated to the internal roughness of the pipe section. This roughness has a direct bearing on the velocity within a line section. Pipe material is also correlated to the pipe section length. Different materials are made in different pipe section lengths. Existing material types include vitrified clay (VC), PVC, CI, DI and concrete pipe. Seventy-eight percent of the sanitary sewer system is comprised of VC pipe. Material types to be used in rehabilitation include PVC, DI, resin-impregnated synthetic fabric and HDPE. All new materials used decrease the coefficient of friction except for DI pipe. PVC pipe is used for all *replacement* and *spot repair* unless there is possible exposure to high temperatures or the depth to pipe is over twelve feet. DI is used in these cases. The resin-impregnated synthetic fabric is used when using the cured-in-place method. HDPE is used when performing *slip-line* or *pipe bursting*.

Pipe diameter is a required parameter needed to calculate the original and revised capacities of a line section. Line sections range from four-to-36 inches in diameter. The diameter of pipe has the greatest bearing on its carrying capacity.

Pipe length is a required parameter needed to calculate the slope of a given line section. Slopes are needed to determine if a line section meets the minimum requirements for velocity and capacity. The pipe length is also necessary to calculate the percentage of defects for a line section. The percentage of defects has a direct bearing on the selected rehabilitation method.

The *upstream manhole invert out* and the *downstream manhole invert in* are used to calculate the vertical fall within a given line section. This vertical fall divided by the line section length is the slope. Slope is used in combination with the roughness coefficient and pipe diameter to calculate the velocity.

Pipe depth is the average depth from the surface down to the invert of the pipe section and is directly proportional to the cost of excavation and the need for sheeting and shoring within the trench.

Pipe location is the area on the Naval Base where the line section physically exist. Locations include: Admirals Row, enlisted housing areas, piers, main roadways, secondary roadways, playgrounds, open fields and roadway intersections. These locations are directly related to political sensitivity, one of the main factors used in selecting a rehabilitation method. Areas such as Admirals Row or piers, for example, have a high level of political sensitivity, whereas an area like an open field has a very low level.

Capacity required is information needed to ensure that the existing pipe meets the needs of the areas it serves now and in the future. *Capacity required* is compared with the actual capacity of the line section.

Surface condition refers to various types of ground material covering line sections such as grass, dirt, gravel, asphalt, concrete and reinforced concrete. The *surface type* has a direct bearing on excavation cost and is used in determining the appropriate rehabilitation method. Naturally, more expense is incurred for line sections under concrete versus grass or dirt.

Development of Knowledge-Based Rules

This knowledge-based system is broken into four major components. They are collection of user input, facts, defaults and rules. Appendix C shows the ten forms in the knowledge-base used to acquire data needed to make a rehabilitation decision. The user input is combined with twenty-two facts to ensure that basic engineering standards are incorporated in the repair selection. The facts are:

- total defect percent
- slope
- velocity
- new velocity
- actual capacity
- new capacity
- iiscore
- pcpercent
- break in service connection score
- protruding service connection score
- leaking service connection score
- abandoned service connection score
- root growth score
- replace score
- spot repair score
- slip-line score
- cured in place score
- pim score
- cross connection score
- mineral deposits score
- corroded pipe score
- change in pipe size score

Defaults ensure that parameters without given data are assigned a value so that all rules in the knowledge base are evaluated. The defaults are:

- repair method
- break in service connection repair
- root growth repair
- mineral deposits repair
- protruding service connection repair

- abandon service connection repair
- corroded pipe repair
- change in pipe size repair

Rules used to make a rehabilitation decision are divided into 21 groups as follows:

- check for adequate capacity
- check for adequate velocity
- material pipe segment length/roughness
- surface condition cost
- political sensitivity of location
- trench cost due to depth
- pipe condition
- infiltration condition
- determination of pre repair method
- selection of mineral deposits repair
- selection of root growth repair
- choice of corroded pipe repair
- change in pipe size repair
- cross connection repair
- break in service connection repair
- protruding service connection repair
- abandon service connection repair
- final repair method
- trench cost score by repair method
- surface cost score by repair method
- political sensitivity score by repair method
- infiltration condition score by repair method

A basis and explanation for all rules are subdivided into nine categories. These areas of consideration adequately identify and assign the values needed to make a repair decision. They are listed below:

- Virginia Department of Health Regulations
- Material Considerations
- Surface Type Considerations
- Location Considerations
- Depth Considerations
- Pipe Condition
- Infiltration Percentage

- Scoring Method to Select Rehabilitation Alternative
- Caveats to Final Repair Method

Virginia Department of Health Regulations

The VDH and DEQ require that all gravity sanitary sewer pipe lines have the required capacity to meet the need of the service area and provide a minimum velocity of two feet per second. This minimum velocity is referred to as the "scouring" velocity and ensures that all material can move down the pipe section. The first two sets of rules, "Capacity Check" and "Velocity Check" in Appendix B, compare the required capacity to the actual capacity of the line section. The common theme throughout most of these rules is the fact that the existing pipe is not PVC. The actual capacity is calculated by multiplying the velocity by the cross sectional area of the pipe. Manning's formula is used to calculate the velocity and includes the variables of slope and roughness as shown below:

velocity = 1.486/roughness(0.5*diameter/12)^0.67*(slope/100)^0.5* (1)

The "Capacity Check" rules specifically address a line section that has inadequate capacity as exemplified below:

if capacity required > actual capacity
and velocity > 2
and material is not "PVC"
and pipe condition is excellent
and new capacity > capacity required
then repair method is "Cured-in-Place"

If the existing pipe is PVC, a line section cannot have increased capacity by reducing the roughness coefficient. PVC pipe also indicates a line section, if replaced, could not go back at the same slope or same size. The final rule for inadequate capacity addresses a line section that is PVC by recommending that the repair method is "Replace and Increase Slope or Replace and Increase Pipe Size". Other factors that directly affect these rules are: percentage of critical defects, surface condition, political sensitivity, depth and new capacity. Political sensitivity has a direct bearing on whether to repair a pipe section by *replacement* or to use a less disruptive repair method such as *pipe bursting*. The percentage of critical defects influences the choice of using trenchless technology in combination with a spot repair or direct replacement as the rehabilitation technique. Surface condition and depth assist in delineating the difference between using direct replacement with increased slope or pipe size versus pipe insertion method with increased pipe size. The new capacity is calculated using a reduced roughness coefficient for the recommended new line section. This differentiates between trenchless or in-place repairs that still would not provide adequate capacity versus repairs that change the slope or increase the pipe diameter size to achieve the needed capacity.

There are rules associated with meeting the minimum required velocity. These rules are affected by material type, pipe condition, required capacity and new velocity. If the pipe material is not PVC, the velocity would possibly be increased by a reduction in the roughness coefficient. If the new velocity is greater than two feet per second, a trenchless repair method is generally preferred. If the new velocity is less than two feet per second, the repair method is "Replace and Increase Slope or Replace and Increase Pipe Size" as shown below:

if velocity < 2
and capacity required < actual capacity
and material is not "PVC"
and pipe condition is excellent
and new velocity < 2
then repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"

Pipe condition affects whether a trenchless repair method in combination with a spot repair is needed, or if replacement should be used. Note that *required capacity* is a basic requirement for this set of rules to be true and ensures that adequate capacity is available within the line section.

Material Considerations

The naval base has five different types of pipe material. They are VC pipe, concrete, DI, CI and PVC. Each material has an associated roughness coefficient and pipe segment length as shown in Table 1. Pipe segment represents the length of pipe that is damaged per defect and is based on the joint length of a given material type and the amount of pipe that must be removed to repair an individual defect. The roughness coefficient is based on the material and is used to calculate the velocity of a line section.

Material Type	Pipe Segment Length	Roughness
Vitrified Clay	3′	0.013
Concrete	6′	0.015
Ductile Iron	20′	0.014
Cast Iron	18′	0.015
Polyvinyl Chloride	6′	0.009

Table 1. Pipe Segment Length & Roughness for Material Types

Surface Type Considerations

Six different types of surfaces with ratings ranging between "very low" and "very high" are shown in Table 2. There is a clear difference, for example, in the cost to remove grass versus reinforced concrete. This difference is illustrated by the fact that grass has a "very low" surface cost and reinforced concrete has a "very high" surface cost. These ratings were determined through group discussions with the experts and are based on heuristics related to excavation of the different surface types.

Surface Type	Rating
Grass	Very Low
Dirt	Low
Gravel	Low
Asphalt	Medium
Concrete	High
Reinforced Concrete	Very High

Table 2. Surface Type Ratings

Location Considerations

Eleven different locations with differing political sensitivities are shown in Table 3. These locations are tied directly to a level of political sensitivity ranging from "very low" to "very high". For example, piers require special consideration for repair due to the high level of activity, whereas an open field reveals no concern for the repair method selected. Naval operations have a large impact on the final rehabilitation method selected. Often times, political concerns affect the mission of the naval base.

Location	Political Sensitivity
Admirals Row	Very High
Willoughby Housing	Medium
Camp Allen Housing	Medium
Armed Forces Staff College	Medium
Ben Moreell Housing	Medium
Piers	Very High
Main Roadway	High
Secondary Roadway	Medium
Playground	Low
Open Field	Very Low
Intersection	High

Table 3. Political Sensitivity for Different Locations

Depth Considerations

Depth has a direct bearing on the cost of excavation. Depths are categorized from "very low" to "very high" based on increasing depth as shown in Table 4. Naturally, the greater the depth of excavation the higher the cost. There are other factors that affect the cost of trenching. According to the Occupational Safety Health Association (OSHA), any trench over five feet in depth is required to have sheeting and shoring to prevent failure of trench walls, or the trench must be cut back at a slope based on the soil conditions encountered. In the case of sheeting and shoring, additional costs are incurred for labor and equipment. Generally, at depths over eight feet, in addition to sheeting and shoring, de-watering is needed to remove water from the ground and stabilize the trench. De-watering increases the amount of labor and equipment necessary to complete the excavation. Finally, depths over twelve feet require larger equipment such as excavators to do the work. The labor dramatically increases in providing access for workers to such a deep trench.

Depth	Trench Cost
<3′	Very Low
3′-5′	Low
5′-8′	Medium
8′-12′	High
>12′	Very High

Table 4. Trench Cost for Different Depths

Pipe Condition

Pipe condition is determined by the number of critical defects found in a line section. *Critical defects* are summed and multiplied by the pipe segment length to determine the total length of critical defects. The percentage of critical defects is determined by dividing by the total length of the line section as shown in the formula below:

$$pcpercent = (horizontal\ misalignment + deformed\ pipe + missing\ pieces + crushed\ pipe + severe\ dips\ in\ line * pipe\ segment)/length * 100 \qquad (2)$$

Pipe conditions are stated from "poor" to "excellent" and based on the value of "pcpercent" as indicated in Table 5.

pcpercent	Pipe Condition
0	Excellent
0-10	Very Good
10-25	Good
25-50	Fair
>50	Poor

Table 5. Pipe Condition for Different Critical Defect Percentages

Pipe condition is important since critical defects preclude repair by a trenchless method such as *cured-in-place* or *slip-line*.

Infiltration Percentage

Infiltration percentage is found the same way as the percentage of critical defects. *Infiltration defects* are summed and multiplied by the pipe segment length. This value is then divided by the total length of the line section as shown below:

*iiscore = (moderate cracked joint + moderate offset joint + moderate open joint + moderate leaking joint + moderate circular cracks + moderate longitudinal cracks + moderate multiple cracks + mineral deposits + root growth + break in service connection + protruding service connection + leaking service connection + abandoned service connection + hole in pipe * pipe segment)/ length * 100* (3)

Infiltration condition is indicated from "very low" to "very high" and based on the value of "iiscore" as shown in Table 6.

iiscore	Infiltration Condition
<10	Very Low
10-25	Low
25-40	Medium
40-60	High
>60	Very High

Table 6. Infiltration Condition for Different Infiltration Percentages

The level of infiltration is important since the naval base can experience three times the normal daily flow during a rain event.

Scoring Method to Select Rehabilitation Alternative

A point scoring system from zero to 100 was developed to determine the most effective rehabilitation method to use knowing the value or sensitivity of a given factor that affects the decision. For example, a value of 50 for slip-lining under medium trench cost means there is a 50% chance that one would use this repair given the value of trench cost without regard to other repair alternatives. The range of possible scores was selected to give ample flexibility in rating each factor for a given rehabilitation alternative. These factors are trench cost, surface cost, political sensitivity and infiltration condition. Values for each rehabilitation method are shown in Tables 7, 8, 9 and 10.

	Very Low	Low	Medium	High	Very High
Replace	100	80	50	10	0
Spot Repr	100	80	50	10	0
Slip-line	20	20	50	60	40
CIP	10	20	60	80	100
PIM	10	20	50	60	40

Table 7. Repair Scores for Different Levels of Trench Cost

	Very Low	Low	Medium	High	Very High
Replace	100	80	50	30	10
Spot Repr	100	80	50	30	10
Slip-line	20	40	60	50	40
CIP	10	20	70	80	100
PIM	20	40	60	50	60

Table 8. Repair Scores for Different Levels of Surface Cost

	Very Low	Low	Medium	High	Very High
Replace	100	90	50	20	10
Spot Repr	100	90	50	20	10
Slip-line	100	95	85	70	40
CIP	100	100	100	100	100
PIM	100	95	85	70	60

Table 9. Repair Scores for Different Levels of Political Sensitivity

	Very Low	Low	Medium	High	Very High
Replace	0	25	50	50	50
Spot Repr	100	75	50	20	0
Slip-line	0	50	50	75	75
CIP	0	50	50	80	100
PIM	0	50	50	70	90

Table 10. Repair Scores for Different Levels of Infiltration Condition

Many heuristics are involved in each decision and the score is assigned based on an individual consideration without regard to other rehabilitation methods. Note that the likelihood of all repair types is very close when the trench cost is medium.

A general trend can be seen for trench and surface cost factors. *Replacement* and *spot repair* values decrease as the cost increases, whereas a trenchless repair method like *cured-in-place* increases as excavation costs increase. *Slip-line* and *pipe bursting* scores level off since excavation for access pits are necessary on either end of a line section.

The section under political sensitivity shows that cured-in-place is a preferred method regardless of the intensity level. Very low levels of political sensitivity have no impact on the appropriate rehabilitation method. Clearly, methods which employ some form of trenchless technology are preferred.

Infiltration condition scores indicate that spot repair is the only preferred method when the number of infiltration defects is very low. As the infiltration condition deteriorates, the use of spot repair diminishes to zero. When the condition is medium any method could be appropriate as a repair technique when viewed on an individual basis. Clearly, infiltration is most preferably handled using some form of trenchless technology.

A pre-repair method is determined by summing the values of each factor corresponding to a given rehabilitation alternative. The method with the highest score is chosen as the pre-repair method. In the case of a tie between repair types, the hierarchy for selection is determined as exemplified below:

if capacity required < actual capacity
and velocity > = 2
and replace score > = spot repair score
and replace score > slip-line score
and replace score > cured in place score
and replace score > pim score
then pre repair method is "Replace"

Essentially, priority is given in the order of replacement, spot repair, slip-line, cured-in-place and pipe bursting.

The final repair method is selected based on the pre-repair method and the percentage of critical defects and/or total defects found in the line section. The total defect percentage is the summation of infiltration and critical defects. If the pre-repair method is "Replace" then obviously the final repair method is "Replace". If "Spot Repair" is the pre-repair method and the total defect percentage is less than 60% then the repair method remains "Spot Repair" otherwise it becomes "Replace". The total percentage of defects is used since the pre-repair method requires excavation. If "Cured-in-Place" is the pre-repair method and the critical defects are less than 30% then the final repair method is "Spot Repair then Cured-in-Place" otherwise it is "Replace". Thirty percent is used because lining is still paid for through the spot repair sections. The same approach is used for *slip-line* as *cured-in-place*. *Pipe bursting* has no regard for critical defects since it destroys the original pipe while inserting the new pipe.

Caveats to Final Repair Method

There are several recommendations that caveat the final repair method. These recommendations address cross connections, break-in service connections, protruding service connections, abandoned service connections, changes in pipe size, corroded pipe, root growth and mineral deposits. Recommendations vary depending on the selected rehabilitation method.

Cross-Connection Recommendations

Cross connection recommendations are based on user input information. Essentially, if a cross-connection exists, the final output indicates that the cross connection should be re-routed without regard to the final repair method. This is an important consideration since direct inflow sources create a higher level of flow during rain events and must be eliminated.

Break-in Service Connection Recommendations

Recommendations for break-in service connections advise the user to excavate and replace all active laterals for "Replace", "Spot Repair", "Slip-line" and "Pipe Insertion Method". These are the only available method since these rehabilitation techniques require some form of excavation and do not lend themselves to a trenchless form of repair. "Cured-in-Place" is the exception since the service connections can be opened using an internal cutter that opens the pipe at the service location. The location is identifiable by television inspection footage showing indentations in the liner surface.

Protruding Connection Recommendations

Protruding service connections are grouped with break-in service connections since excavation is required for repair. The lone exception is "Cured-in-Place" since an internal grinder can be used to make the lateral flush with the inside wall of the pipe section. Once flush, the lateral can be opened using the internal cutter.

Abandoned Connection Recommendations

This recommendation is just a reminder to the user to properly excavate and abandon all inactive laterals when using "Replace" or "Spot Repair". For "Slip-line" and "Pipe Insertion Method", the user is reminded not to excavate the lateral and reconnect. The "Cured-in-Place" repair method is approached by cautioning that abandoned laterals should not be cut open, effectively eliminating any infiltration into the repaired line from old laterals.

Change in Pipe Size Recommendation

This recommendation ensures that all changes in pipe size are addressed so that no reductions in pipe size are encountered in the rehabilitated line that may cause a blockage. In general, the smaller pipe size takes up a lesser percentage of the overall line; therefore, this basic assumption is built into the system. "Cured-in-Place" and "Slip-line" methods require that the smaller pipe size be excavated and replaced prior to starting. The user is reminded to excavate and repair the smaller pipe size for those lines recommended for "Spot Repair". "Replace" and "Pipe Insertion Method" automatically address the problem of smaller pipe size. The user is merely reminded of this fact.

Corroded Pipe Recommendations

Corroded pipe is a function of the cleanliness of the pipe section and is most often found in DI and CI line sections. "Replace" and "Pipe Insertion Method" do not take into account corroded pipe since the line section is being replaced. When methods like "Slip-line" and "Cured-in-Place" are used, the user is reminded that the pipe must be thoroughly cleaned before using the repair process. This cleaning is essential to ensure that area is optimized in the case of cured-in-place pipe and that minimal capacity is lost so that the next lowest diameter of pipe can be used for slip-lining. When "Spot Repair" is selected, the user is again reminded to thoroughly clean the pipe so that flow can be maximized and laminar through the existing pipe.

Root Growth Recommendations

Root growth is a natural consequence of trees growing near the sewer line section. Over the course of time, roots work their way into the individual joints of a line section causing excessive infiltration into the system and blockage. "Repair" and "Pipe Insertion Method" effectively eliminate this problem since the line section is new. "Spot Repair' reminds the user that all roots should be removed away from those pipe sections that are being repaired. "Slip-line" and "Cured-in-Place" are the most critical methods for requiring that all the roots are removed. Roots can be removed by using an internal root cutter. Roots left in the line section could "catch" the slip-line pipe and make excavation necessary to fix the problem, or they could cause irregularities in cured-in-place pipe that may hinder proper flow.

Mineral Deposit Recommendations

Mineral deposits form on the inside of the pipe section. These deposits often inhibit flow and create obstructions that make video inspections difficult. Generally, mineral deposits remaining in the line increase in size over time. The recommendations appropriately reflect the importance of resolving this problem. Thorough cleaning is needed for both "Slip-line" and "Cured-in-Place" before either process. The same difficulties are encountered as in root growth if proper cleaning is not used. "Pipe Insertion Method" and "Replace require no special treatment because the line section is new. "Spot Repair" indicates that all mineral deposits should be properly removed when replacing the pipe sections.

CHAPTER 6

EVALUATION AND VALIDATION OF KNOWLEDGE-BASE

The evaluation and validation process was a constant factor throughout the development of the knowledge-based system. The initial concept was to use a decision tree to model the process for making repair decisions. This method was effective in determining the different scenarios involved in making a rehabilitation decision when considering required capacity and minimum velocity. However, the decision tree had limited effectiveness since many factors including depth, surface condition and location would require a decision tree of an unmanageable size. Simplification was needed to efficiently develop the knowledge base. Many iterations led to the development of a scoring system that evaluates rehabilitation techniques given certain factors as discussed in Chapter 4.

This improvement simplified the process without sacrificing flexibility in decision making and was subsequently verified by extensive testing by the experts. Testing consisted of comparative analysis with historical repair decisions and those found using the expert system. Some minor adjustments were made on the scores based on findings from the testing.

Originally, critical defects were included with the other four factors. It was discovered that the entire spectrum of repair methods could not be addressed using this method; in particular, spot repairs in combination with "Slip-line" and "Cured-in-Place" methods. Therefore, a pre-repair method was used based on the other four factors and a final repair method was considered based on the pre-repair method in combination with the critical defect percentage. This allowed the flexibility of selecting an appropriate repair method without greatly increasing the number of possibilities in the scoring system. This dramatic increase would be based on having to consider the different combination of infiltration defects with critical defects. This would increase the size of the table by five times. The other difficulty was trying to combine a trenchless repair with spot repair when considering the first four factors. These factors are scored based on the inherent and heuristic values associated with each rehabilitation alternative. Therefore, it was best to consider the first four factors together and let critical defects influence the final recommendation.

Cost is evaluated under the surface and trench cost categories. However, political sensitivity takes into account the importance of not inhibiting the mission of the naval base. Infiltration and critical defects properly account for the condition of the pipe. All factors being important, each category was assigned an equal weighting. Therefore, cost is not the controlling factor in the decision making process. It is meant to be an equal assessment of all factors.

Finally, rules were created to choose the appropriate caveats associated with the different repair alternatives. The form of the final output was made so that each additional part of the final solution could be listed regardless of the rehabilitation decision. Overall, the above process greatly reduced the number of rules and repetitiveness of the knowledge base.

Continued testing and the use of "what if" scenarios showed that occasionally the expert would choose a method different than the knowledge base. This was expected since the knowledge base was created from a consensus of four experts and individuals often vary from the average in their own decision-making process. When looking at the differences in the decision, it was clear that the differences were minimal between the two alternatives and either might have been used without great consequence.

The continuous testing assured a system that effectively and accurately reflects the general decision making process of the Utility Department. The most useful part of this system is its flexibility in the scoring system. Changes can be made to accommodate different group concerns, reflecting their differing priorities. Additionally, the system is designed so that information can be evaluated on a qualitative basis that is correlated into a quantitative basis. This is useful when presenting the rationale behind the decision to executives who are more interested in qualitative heuristics versus hard core numbers.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

Simplicity is the most valuable asset of this knowledge-based system. Essentially, the system evaluates one line section at a time based on user input. This system allows someone with little experience to enter the data and obtain a rehabilitation solution. These line sections can then be combined to make an overall assessment of a flow area.

The developed knowledge-based system is expected to provide many economic and operational benefits. Increased repair decisions, over time, reduce the cost from inflation and decrease the possibility of a costly pipeline collapse. A resultant increase in construction deters and possibly averts costly fines for non-compliance by HRSD. Operational aspects should be improved since repairs are being made proactively, allowing more time for future planning and leading to a more organized structure for preventative maintenance. Additional benefits include a more consistent and accurate decision-making process and a tool that can be used to train personnel in proper wastewater system repair.

Future improvements should include a knowledge base that can interface and assimilate information for a flow area from a database, make individual repair decisions and then make final recommendations based on the overall set of recommendations for the flow area. This will allow for an overall continuity of repair types within a given flow area. Additional improvement to the knowledge-based system may include a numerical response to the final solution which may include pipe sizes and proposed new invert elevations for the line section. The program can also be enhanced to recommend re-routing of the system based on some form of nodal analysis.

Training for this expert system includes a basic understanding of the shell XI-Plus® and a familiarity with data input and its implications. Output is explained and the user is shown how to track the decision-making process to ensure the proper entry of all data based on given conclusions. The program is used in the design process to demonstrate how different factors may affect the outcome. In other words, the program is used as a design tool outside of the PWC Utility Department. This is applicable in cases where a study and design are done concurrently. The expected resultant is a cost savings in design and review time.

BIBLIOGRAPHY

Capone, Thomas E. "Microcomputers Can Aid in Sanitary Sewer System Analysis and Design" Public Works Journal (1988) vol. 119, pp. 71-74.

Clendaniel, B. and Soltesz, J. E. "Seattle Automates Sewer Inspection and Maintenance" Public Works Journal (1986) vol. 120, pp.74-75.

Desher, Drew P. and Davis, Patrick K. "Designing Sanitary Sewer with Microcomputers" Journal of Environmental Engineering (1988) vol. 114, pp. 721-727.

Gray, Jonathan P. "Computer Package Helps City Manage Sewer System" Public Works Journal (1988) vol. 119, pp. 52-54.

Gregory Jr., H. N. and Hansen, C. A. "New Technologies Help Houston Inspect its Sewers" Public Works Journal (1990) vol. 121, pp. 58-60.

Lindeburg, Michael R. Engineer-in-Training Reference Manual. Belmont, CA: Professional Publications, Inc., 1992.

Montgomery Watson Engineers Infiltration/Inflow Study at the Norfolk Naval Shipyard. (Herndon, 1994).

Patton, Harris, Rust and Associates Infiltration-Inflow Study at Norfolk Naval Base (Norfolk, 1991), vol. 1.

Schaaf, James R. "Computerization of Sewer Maintenance Scheduling" Public Works Journal (1985) vol. 116, pp. 128-129.

Tekel, Sahim and Belkaya, Huseyin "Computerized Layout Generation for Sanitary Sewers" Journal of Water Resources Planning and Management (1986) vol. 112, pp. 500-515.

Turban, Efraim Expert Systems and Applied Artificial Intelligence. New York, NY: Macmillan Publishing Company, 1992.

Urquhart, Leonard C. Civil Engineering Handbook. New York, NY: McGraw-Hill Book Company, Inc., 1962.

Virginia Department of Health. Sewage Collection and Treatment Regulations. (Norfolk, 1993) Part 3, Article 1.

Waterman, Donald A. A Guide to Expert Systems. New York, NY: Addison-Wesley Publishing Company, 1989.

APPENDIX A

Definition of Terminology

Artificial Intelligence (AI)

The branch of computer science devoted to the study of how computers can be used to simulate or duplicate functions of the human brain.

Broken Pipe

A pipe is considered broken when a relatively large portion of the pipe is missing. The broken portions of pipe are sources of excessive infiltration and can cause blockage.

Circular Cracked Pipe

Cracks observed in sewer lines that follow a portion of the total circumference of the pipe. Such cracks can be a source of infiltration.

Cracked Joint

Joints in a given sewer line section that are properly aligned, but are cracked and may allow infiltration to occur.

Critical Defect

Any defect that causes an obstruction or inhibits flow within the existing pipe.

Crushed Pipe

When the pipe is crushed or collapsed. This can be cause for excessive infiltration and possible blockage.

Decision Tree

A graphical structure of nodes and arcs or lines that shows the alternative paths for various decisions or programs.

Default

A pre-defined value for variables that may or may not be assigned a value by the user.

Dip-in-Line

When a portion of the line is observed to be vertically misaligned indicating structural deterioration. Dips can cause infiltration, blockages in pipes and may even lead to collapse.

Expert

A person who, through training and experience, can perform a task with a degree of skill that is beneficial to capture and distribute. The person filling this role is usually a top-level task performer.

Expert System Shell

A software tool designed to simplify the development of an expert system. Any program that permits the creation of an expert system without having to program all elements of it from scratch.

Fact

A known value or equation used in a knowledge-based system.

Heuristics

Anything that helps a human or computer to discover or learn. The use of empirical knowledge to aid in problem solving. Rules of thumb, tricks, procedural tips, and other information that help to guide, limit and speed up the search process.

Infiltration

The water entering a sewer system and service connection from the ground by such means as defective pipe or pipe joints.

Inflow

The water discharged into a sewer system and service connection from such sources as roof leaders, catch basins, yard inlets or manhole covers.

Interface

That facility of a computer system or program that links with other application systems, or a facility of a computer program that interacts with both the computer user and the remainder of the computer system.

Knowledge

Understanding, awareness, or familiarity acquired through education or experience. Anything that has been learned, perceived, inferred, and understood.

Knowledge Acquisition

The process by which Knowledge Based System developers find the knowledge: facts, rules, heuristics and procedures that the domain experts use to perform the task of interest. Knowledge acquisition usually is accomplished by meetings between knowledge engineers and domain experts at which knowledge engineers attempt to capture the expert's knowledge.

Knowledge Base

A collection of data, rules, inferences and procedures organized into production rules or other formats. The assembly of all the information and knowledge of a specific field of interest that forms the basis for and intelligent computer system.

Knowledge Based System (KBS)

An advanced computer program that can, at a high level of competence, solve difficult problems requiring the use of expertise and experience. It accomplishes this by employing knowledge of the techniques, information, heuristics and problem solving processes that are used by human experts to solve such problems. Knowledge Based Systems thus provide a way to store human knowledge, expertise and experience in computers. The term KBS is often used as a synonym for expert system.

Leaking Joint

Any joint which may otherwise be properly aligned, but is observed to be contributing infiltration.

Leaking Service Connection

When infiltration is observed to be entering the sewer, not from the service lateral, but from the actual connection where the service lateral joins the sewer line.

Longitudinal Cracked Pipe

A crack in a sewer pipe which extends lengthwise through a portion of the pipe. Such cracks can allow infiltration to occur or can lead to collapsed pipes.

Multiple Cracks

When two or more cracks are observed in a sewer pipe which extends lengthwise through a portion of pipe. Such cracks can allow infiltration to occur or can lead to collapsed pipes.

Offset Joint

When a joint is observed to be misaligned but not necessarily open. Offset joints can be contributors of infiltration.

Protruding Service Connection

Those service laterals that are observed to be protruding into the sewer line. The can prevent the passage of internal inspection equipment through the line. They can also cause blockage and restrictions of flow.

Root Growth

Roots protruding into sewer sections can contribute infiltration or cause blockages and restrictions of flow.

Rules

Statements within a knowledge-base in the form of "If"{value}, "then" {outcome}.

Slope

The slant or inclination downward of a sewer pipeline. This is typically calculated by dividing the change in elevation from one end of the pipe to the other by the total length.

Standard Dimension Ratio

This is the ratio of pipe diameter size to pipe wall thickness in a sewer pipe.

Wastewater

The spent or used water of a community or industry which contains dissolved and suspended matter.

APPENDIX B

Rules For Knowledge-Based System

"Forms-User Input"

```
when query pipe segment
then do form "cctv defects - 1"
 and do form pipe material
 and do form pipe diameter
 and do form pipe length
 and do form pipe invert out
 and do form pipe invert in
  and do form pipe depth
 and do form pipe location
 and do form capacity required
 and check pre repair method
 and check total defect percent
 and check political sensitivity
 and check material
 and check pipe condition
 and check depth
 and check surface
 and check slope
 and check velocity
 and check capacity required
 and check actual capacity
 and check iiscore
 and check pcpercent
 and check new velocity
 and check new capacity
 and check repair method
 and check break in service connection score
 and check leaking service connection score
 and check protruding service connection score
 and check abandoned service connection score
 and check break in service connection repair
 and check protruding service connection repair
 and check abandon service connection repair
 and check change in pipe size score
```

and check change in pipe size repair
and check mineral deposits score
and check mineral deposits repair
and check root growth score
and check root growth repair
and check corroded pipe score
and check corroded pipe repair
and check cross connection score
and check cross connection repair
and do form final report

"Facts"

fact total defect percent = iiscore + pcpercent

fact slope = (pipe invert out - pipe invert in) / length * 100

fact velocity = 1.486 / roughness * (0.5 * diameter / 12) ^ 0.67 * (slope / 100) ^ 0.5

fact new velocity = 1.486 / 0.009 * (0.5 * diameter / 12) ^ 0.67 * (slope / 100) ^ 0.5

fact actual capacity = velocity * 3.1415 * (diameter / 12) ^ 2 / 4 * 448

fact new capacity = new velocity * 3.1415 * (diameter / 12) ^ 2 / 4 * 448

fact iiscore = (moderate cracked joint + moderate offset joint + moderate open joint + moderate leaking joint + moderate circular cracks + moderate longitudinal cracks + moderate multiple cracks + mineral deposits + root growth + break in service connection + protruding service connection + leaking service connection + abandoned service connection + hole in pipe * pipe segment) / length * 100

fact pcpercent = (horizontal misalignment + deformed pipe + missing pieces + crushed pipe + severe dips in line * pipe segment) / length * 100

fact break in service connection score = break in service connection

fact protruding service connection score = protruding service connection

fact leaking service connection score = leaking service connection

fact abandoned service connection score = abandoned service connection fact root growth score = root growth

fact replace score = trench cost replace score + surface cost replace score + political sensitivity replace score + ii condition replace score

fact spot repair score = trench cost spot repair score + surface cost spot repair score + political sensitivity spot repair score + ii condition spot repair score

fact slipline score = trench cost slipline score + surface cost slipline score + political sensitivity slipline score + ii condition slipline score

fact cured in place score = trench cost cured in place score + surface cost cured in place score + political sensitivity cured in place score + ii condition cured in place score

fact pim score = trench cost pim score + surface cost pim score + political sensitivity pim score + ii condition pim score

fact cross connection score = cross connection

fact mineral deposits score = mineral deposits

fact corroded pipe score = corroded pipe

fact change in pipe size score = change in pipe size

"Defaults"

default repair method is "Not Enough User Information"

default break in service connection repair is "No Break-In Service Connections Present"

default root growth repair is "No Root Growth Present"

default mineral deposits repair is "No Mineral Deposits Present"

default protruding service connection repair is "Protruding Service Connection Included with Break-in Connections"

default abandon service connection repair is "No Abandoned Service Connection Present"

default corroded pipe repair is "No Corroded Pipe Present" default change in pipe size repair is "No Change in Pipe Size Present"

"Capacity Check"

```
if  capacity required > actual capacity
 and velocity > 2
 and material is not "PVC"
 and pipe condition is excellent
 and new capacity > capacity required
then repair method is "Cured-in-Place"

if  capacity required > actual capacity
 and material is not "PVC"
 and pcpercent < 10
 and pcpercent > 0
 and new capacity > capacity required
then repair method is "Spot Repair then Cured-in-Place"

if  capacity required > actual capacity
 and material is not "PVC"
 and pcpercent >= 10
 and pcpercent < 25
 and new capacity > capacity required
then repair method is "Replace"

if  capacity required > actual capacity
 and material is not "PVC"
 and new capacity < capacity required
 and depth > 8
 and surface is not "Grass"
 and surface is not "Dirt"
 and surface is not "Gravel"
 and velocity > 2
then repair method is "Use Pipe Insertion Method and Increase Pipe Size"

if  capacity required > actual capacity
 and material is not "PVC"
 and new capacity < capacity required
 and depth < 8
 and political sensitivity is not very low
 and political sensitivity is not low
 and political sensitivity is not medium
then repair method is "Use Pipe Insertion Method and Increase Pipe Size"

if  capacity required > actual capacity
 and material is not "PVC"
```

and surface is "Grass" or "Dirt" or "Gravel"
and political sensitivity is very low or low or medium
and new capacity < capacity required
then repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"

if capacity required > actual capacity
and material is "PVC"
then repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"

"Velocity Check"

if velocity < 2
and capacity required < actual capacity
and material is not "PVC"
and pcpercent = 0
and new velocity > 2
then repair method is "Cured-in-Place"

if velocity < 2
and capacity required < actual capacity
and material is not "PVC"
and pcpercent > 0
and pcpercent < 10
and new velocity > 2
then repair method is "Spot Repair then Cured-in-Place"

if velocity < 2
and capacity required < actual capacity
and material is not "PVC"
and pcpercent > 25
and new velocity > 2
then repair method is "Replace"

if velocity < 2
and capacity required < actual capacity
and material is not "PVC"
and pipe condition is excellent
and new velocity < 2
then repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"

if velocity < 2
and capacity required < actual capacity
and material is not "PVC"

and pipe condition is not excellent
and new velocity < 2
then repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"

"Materials"

if material is "Clay"
then pipe segment = 3
and roughness = 0.013

if material is "Concrete"
then pipe segment = 6
and roughness = 0.015

if material is "Ductile Iron"
then pipe segment = 20
and roughness = 0.014

if material is "Cast Iron"
then pipe segment = 18
and roughness = 0.015

if material is "PVC"
then pipe segment = 6
and roughness = 0.009

"Surface Cost"

if surface is "Grass"
then surface cost is very low

if surface is "Dirt"
then surface cost is low

if surface is "Gravel"
then surface cost is low

if surface is "Asphalt"
then surface cost is medium

if surface is "Concrete"
then surface cost is high

if surface is "Reinforced Concrete"
then surface cost is very high

"Political Sensitivity"

if location is "Admirals Row"
then political sensitivity is very high

if location is "Willoughby Housing"
then political sensitivity is medium

if location is "Camp Allen Housing"
then political sensitivity is medium

if location is "AFSC Housing"
then political sensitivity is medium

if location is "Ben Moreell Housing"
then political sensitivity is medium

if location is "Piers"
then political sensitivity is very high

if location is "Main Roadway"
then political sensitivity is high

if location is "Secondary Roadway"
then political sensitivity is medium

if location is "Playground"
then political sensitivity is low

if location is "Open Field"
then political sensitivity is very low

if location is "Roadway Intersection"
then political sensitivity is high

"Depth"

if depth < 3
then trench cost is very low cost

if depth > = 3
and depth < 5
then trench cost is low cost

if depth > = 5
and depth < 8
then trench cost is medium cost

if depth > = 8
and depth < 12
then trench cost is high cost

if depth > = 12
then trench cost is very high cost

"Pipe Condition"

if pcpercent = 0
then pipe condition is excellent

if pcpercent > 0
and pcpercent < = 10
then pipe condition is very good

if pcpercent > 10
and pcpercent < = 25
then pipe condition is good

if pcpercent > 25
and pcpercent < = 50
then pipe condition is fair

if pcpercent > 50
then pipe condition is poor

"Infiltration Percentage"

if iiscore < 10
then ii condition is very low ii

if iiscore > = 10
and iiscore < 25
then ii condition is low ii

if iiscore > = 25
and iiscore < 40
then ii condition is medium ii

if iiscore > = 40
and iiscore < 60
then ii condition is high ii

if iiscore > = 60
then ii condition is very high ii

"Trench Cost Scores"

if trench cost is very low cost
then trench cost replace score = 100

if trench cost is low cost
then trench cost replace score = 80

if trench cost is medium cost
then trench cost replace score = 50

if trench cost is high cost
then trench cost replace score = 10

if trench cost is very high cost
then trench cost replace score = 0

if trench cost is very low cost
then trench cost spot repair score = 100

if trench cost is low cost
then trench cost spot repair score = 80

if trench cost is medium cost
then trench cost spot repair score = 50

if trench cost is high cost
then trench cost spot repair score = 10

if trench cost is very high cost
then trench cost spot repair score = 0

if trench cost is very low cost
then trench cost slipline score = 20

if trench cost is low cost
then trench cost slipline score = 20

if trench cost is medium cost
then trench cost slipline score = 50

if trench cost is high cost
then trench cost slipline score = 60

if trench cost is very high cost
then trench cost slipline score = 40

if trench cost is very low cost
then trench cost cured in place score = 10

if trench cost is low cost
then trench cost cured in place score = 20

if trench cost is medium cost
then trench cost cured in place score = 60

if trench cost is high cost
then trench cost cured in place score = 80

if trench cost is very high cost
then trench cost cured in place score = 100

if trench cost is very low cost
then trench cost pim score = 10

if trench cost is low cost
then trench cost pim score = 20

if trench cost is medium cost
then trench cost pim score = 50

if trench cost is high cost
then trench cost pim score = 60

if trench cost is very high cost
then trench cost pim score = 40

"Surface Cost Scores"

if surface cost is very low
then surface cost replace score = 100

if surface cost is low
then surface cost replace score = 80

if surface cost is medium
then surface cost replace score = 50

if surface cost is high
then surface cost replace score = 30

if surface cost is very high
then surface cost replace score = 10

if surface cost is very low
then surface cost spot repair score = 100

if surface cost is low
then surface cost spot repair score = 80

if surface cost is medium
then surface cost spot repair score = 50

if surface cost is high
then surface cost spot repair score = 30

if surface cost is very high
then surface cost spot repair score = 10

if surface cost is very low
then surface cost slipline score = 20

if surface cost is low
then surface cost slipline score = 40

if surface cost is medium
then surface cost slipline score = 60

if surface cost is high
then surface cost slipline score = 50

if surface cost is very high
then surface cost slipline score = 50

if surface cost is very low
then surface cost cured in place score = 10

if surface cost is low
then surface cost cured in place score = 20

if surface cost is medium
then surface cost cured in place score = 70

if surface cost is high
then surface cost cured in place score = 90

if surface cost is very high
then surface cost cured in place score = 100

if surface cost is very low
then surface cost pim score = 20

if surface cost is low
then surface cost pim score = 40

if surface cost is medium
then surface cost pim score = 60

if surface cost is high
then surface cost pim score = 50

if surface cost is very high
then surface cost pim score = 50

"Political Sensitivity Scores"

if political sensitivity is very low
then political sensitivity replace score = 100

if political sensitivity is low
then political sensitivity replace score = 90

if political sensitivity is medium
then political sensitivity replace score = 50

if political sensitivity is high
then political sensitivity replace score = 20

if political sensitivity is very high
then political sensitivity replace score = 10

if political sensitivity is very low
then political sensitivity spot repair score = 100

if political sensitivity is low
then political sensitivity spot repair score = 90

if political sensitivity is medium
then political sensitivity spot repair score = 50

if political sensitivity is high
then political sensitivity spot repair score = 20

if political sensitivity is very high
then political sensitivity spot repair score = 10

if political sensitivity is very low
then political sensitivity slipline score = 100

if political sensitivity is low
then political sensitivity slipline score = 95

if political sensitivity is medium
then political sensitivity slipline score = 85

if political sensitivity is high
then political sensitivity slipline score = 70

if political sensitivity is very high
then political sensitivity slipline score = 40

if political sensitivity is very low
then political sensitivity cured in place score = 100

if political sensitivity is low
then political sensitivity cured in place score = 100

if political sensitivity is medium
then political sensitivity cured in place score = 100

if political sensitivity is high
then political sensitivity cured in place score = 100

if political sensitivity is very high
then political sensitivity cured in place score = 100

if political sensitivity is very low
then political sensitivity pim score = 100

if political sensitivity is low
then political sensitivity pim score = 95

if political sensitivity is medium

then political sensitivity pim score = 85

if political sensitivity is high
then political sensitivity pim score = 70

if political sensitivity is very high
then political sensitivity pim score = 60

"Infiltration Condition Scores"

if ii condition is very low ii
then ii condition replace score = 0

if ii condition is low ii
then ii condition replace score = 25

if ii condition is medium ii
then ii condition replace score = 50

if ii condition is high ii
then ii condition replace score = 50

if ii condition is very high ii
then ii condition replace score = 50

if ii condition is very low ii
then ii condition spot repair score = 100

if ii condition is low ii
then ii condition spot repair score = 75

if ii condition is medium ii
then ii condition spot repair score = 50

if ii condition is high ii
then ii condition spot repair score = 20

if ii condition is very high ii
then ii condition spot repair score = 0

if ii condition is very low ii
then ii condition slipline score = 0

if ii condition is low ii
then ii condition slipline score = 50

if ii condition is medium ii
then ii condition slipline score = 50

if ii condition is high ii
then ii condition slipline score = 75

if ii condition is very high ii
then ii condition slipline score = 75

if ii condition is very low ii
then ii condition cured in place score = 0

if ii condition is low ii
then ii condition cured in place score = 50

if ii condition is medium ii
then ii condition cured in place score = 50

if ii condition is high ii
then ii condition cured in place score = 90

if ii condition is very high ii
then ii condition cured in place score = 100

if ii condition is very low ii
then ii condition pim score = 0

if ii condition is low ii
then ii condition pim score = 50

if ii condition is medium ii
then ii condition pim score = 50

if ii condition is high ii
then ii condition pim score = 70

if ii condition is very high ii
then ii condition pim score = 90

"Pre-Repair Method"

if capacity required < actual capacity
and velocity > = 2
and iiscore > 0
and pipe condition is not excellent
and replace score > = spot repair score

```
 and replace score > = slipline score
 and replace score > = cured in place score
 and replace score > = pim score
then pre repair method is "Replace"

if  capacity required < actual capacity
 and velocity > = 2
 and replace score < spot repair score
 and spot repair score > = slipline score
 and spot repair score > = cured in place score
 and spot repair score > = pim score
then pre repair method is "Spot Repair"

if  capacity required < actual capacity
 and velocity > = 2
 and replace score < slipline score
 and spot repair score < slipline score
 and slipline score > = cured in place score
 and slipline score > = pim score
then pre repair method is "Slipline"

if  capacity required < actual capacity
 and velocity > = 2
 and replace score < cured in place score
 and spot repair score < cured in place score
 and slipline score < cured in place score
 and cured in place score > = pim score
then pre repair method is "Cured-in-Place"

if  capacity required < actual capacity
 and velocity > = 2
 and replace score < pim score
 and spot repair score < pim score
 and slipline score < pim score
 and cured in place score < pim score
then repair method is "Pipe Insertion Method"
```

"Mineral Deposit Repair"

```
if  repair method is "Cured-in-Place"
 and mineral deposits > 0
then mineral deposits repair is "Heavy Cleaning Needed for Mineral Deposits"

if  repair method is "Slipline"
 and mineral deposits > 0
then mineral deposits repair is "Heavy Cleaning Needed for Mineral Deposits"
```

if repair method is "Spot Repair then Cured-in-Place"
and mineral deposits > 0
then mineral deposits repair is "Heavy Cleaning Needed for Mineral deposits"

if repair method is "Spot Repair"
and mineral deposits > 0
then mineral deposits repair is "Ensure Proper Removal of All Mineral Deposits"

if repair method is "Replace"
and mineral deposits > 0
then mineral deposits repair is "Heavy Cleaning Not Needed Since Replacing"

if repair method is "Use Pipe Insertion Method and Increase Pipe Size"
and mineral deposits > 0
then mineral deposits repair is "Heavy Cleaning Not Needed Since Using Pipe Insertion Method"

if repair method is "Pipe Insertion Method"
and mineral deposits > 0
then mineral deposits repair is "Heavy Cleaning Not Needed Since Using Pipe Insertion Method"

if repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"
and mineral deposits score > 0
then mineral deposits repair is "Heavy Cleaning Not Needed Since Replacing"

"Root Growth Repair"

if repair method is "Cured-in-Place"
and root growth > 0
then root growth repair is "Heavy Cleaning Needed for Root Growth"

if repair method is "Slipline"
and root growth > 0
then root growth repair is "Heavy Cleaning Needed for Root Growth"

if repair method is "Spot Repair then Cured-in-Place"
and root growth > 0
then root growth repair is "Heavy Cleaning Needed for Root Growth"

if repair method is "Spot Repair"
and root growth > 0
then root growth repair is "Ensure Proper Removal of Roots Around Pipe Sections"

if repair method is "Replace"
and root growth > 0
then root growth repair is "Heavy Cleaning Not Needed Since Replacing"

if repair method is "Use Pipe Insertion Method and Increase Pipe Size"
and root growth > 0
then root growth repair is "Heavy Cleaning Not Needed Since Using Pipe Insertion Method"

if repair method is "Pipe Insertion Method"
and root growth > 0
then root growth repair is "Heavy Cleaning Not Needed Since Using Pipe Insertion Method"

if repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"
and root growth score > 0
then root growth repair is "Heavy Cleaning Not Needed Since Replacing"

"Corroded Pipe Repair"

if repair method is "Cured-in-Place"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Needed for Corroded Pipe"

if repair method is "Slipline"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Needed for Corroded Pipe"

if repair method is "Spot Repair then Cured-in-Place"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Needed for Corroded Pipe"

if repair method is "Spot Repair"
and corroded pipe score > 0
then corroded pipe repair is "Ensure All Corroded Pipe has been Removed"

if repair method is "Replace"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Not Needed Since Replacing"

if repair method is "Use Pipe Insertion Method and Increase Pipe Size"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Not Needed Since Using Pipe Insertion Method"

if repair method is "Pipe Insertion Method"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Not Needed Since Using Pipe Insertion Method"

if repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"
and corroded pipe score > 0
then corroded pipe repair is "Heavy Cleaning Not Needed Since Replacing"

"Change in Pipe Size Repair"

if repair method is "Cured-in-Place"
and change in pipe size score > 0
then change in pipe size repair is "Perform Spot Repair on Smaller Pipe Size"

if repair method is "Slipline"
and change in pipe size score > 0
then change in pipe size repair is "Perform Spot Repair on Smaller Pipe Size"

if repair method is "Spot Repair"
and change in pipe size score > 0
then change in pipe size repair is "Perform Spot Repair on Smaller Pipe Size"

if repair method is "Spot Repair then Cured-in-Place"
and change in pipe size score > 0
then change in pipe size repair is "Perform Spot Repair on Smaller Pipe Size"

if repair method is "Replace"
and change in pipe size score > 0
then change in pipe size repair is "Replacement will Resolve Change in Pipe Size Problem"

if repair method is "Use Pipe Insertion Method and Increase Pipe Size"
and change in pipe size score > 0
then change in pipe size repair is "Pipe Insertion Method will Resolve Change in Pipe Size Problem"

if repair method is "Pipe Insertion Method"
and change in pipe size score > 0
then change in pipe size repair is "Pipe Insertion Method will Resolve Change in Pipe Size"

if repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"
and change in pipe size score > 0
then change in pipe size repair is "Replacement will Resolve Change in Pipe Size"

"Cross Connection Repair"

if cross connection score > 0
then cross connection repair is "Reroute the Storm Drain Cross-Connection"

"Break in Service Repair"

if repair method is "Pipe Insertion Method"
and break in service connection score + protruding service connection score + leaking service connection score > 0
then break in service connection repair is "Excavate and Reconnect all Active Laterals"

if repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"
and break in service connection score + protruding service connection score + leaking service connection score > 0
then break in service connection repair is "Reconnect all Active Laterals"

if repair method is "Replace"
and break in service connection score + protruding service connection score + leaking service connection score > 0
then break in service connection repair is "Reconnect all Active Laterals"

if repair method is "Slipline"
and break in service connection score + protruding service connection score + leaking service connection score > 0
then break in service connection repair is "Excavate and Reconnect all Active Laterals"

if repair method is "Spot Repair"
and break in service connection score + protruding service connection score + leaking service connection score > 0
then break in service connection repair is "Replace all Break-in Service Connections with PVC Wyes"

if repair method is "Spot Repair then Cured-in-Place"
and break in service connection score + leaking service connection score > 0
then break in service connection repair is "Cut Open Active Lateral Connections"

if repair method is "Use Pipe Insertion Method and Increase Pipe Size"
and break in service connection score + protruding service connection score + leaking service connection score > 0
then break in service connection repair is "Excavate and Reconnect all Active Laterals"

if repair method is "Cured-in-Place"
and break in service connection score + leaking service connection score > 0
then break in service connection repair is "Cut Open Active Lateral Connections"

"Protruding Service Connection Repair"

if repair method is "Cured-in-Place"
and protruding service connection score > 0
then protruding service connection repair is "Grind Down Tap before Using Cured-in-Place"

if repair method is "Spot Repair then Cured-in-Place"
and protruding service connection score > 0
then protruding service connection repair is "Grind Down Tap before Using Cured-in-Place"

"Abandoned Service Connection Repair"

if repair method is "Cured-in-Place"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Cut Open Abandoned Laterals"

if repair method is "Pipe Insertion Method"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Reconnect Abandoned Laterals".

if repair method is "Replace and Increase Slope or Replace and Increase Pipe Size"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Reconnect Abandoned Laterals"

if repair method is "Replace"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Reconnect Abandoned Laterals"

if repair method is "Slipline"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Reconnect Abandoned Laterals"

if repair method is "Spot Repair"
and abandoned service connection score > 0
then abandon service connection repair is "Properly Abandoned Inactive Service Connections"

if repair method is "Spot Repair then Cured-in-Place"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Cut Open Abandoned Lateral Connections"

if repair method is "Use Pipe Insertion Method and Increase Pipe Size"
and abandoned service connection score > 0
then abandon service connection repair is "Do Not Reconnect Abandon Laterals"

"Final Repair Method"

if pre repair method is "Replace"
then repair method is "Replace"

if pre repair method is "Spot Repair"
and total defect percent > 60
then repair method is "Replace"

if pre repair method is "Spot Repair"
and total defect percent < = 60
then repair method is "Spot Repair"

```
if  pre repair method is "Cured-in-Place"
 and pcpercent = 0
then repair method is "Cured-in-Place"

if  pre repair method is "Cured-in-Place"
 and pcpercent > 0
 and pcpercent < = 30
then repair method is "Spot Repair then Cured-in-Place"

if  pre repair method is "Cured-in-Place"
 and pcpercent > 30
then repair method is "Replace"

if  pre repair method is "Slipline"
 and pcpercent = 0
then repair method is "Slipline"

if  pre repair method is "Slipline"
 and pcpercent > 0
 and pcpercent < = 30
then repair method is "Spot Repair then Slipline"

if  pre repair method is "Slipline"
 and pcpercent > 30
then repair method is "Replace"
```

APPENDIX C

User Input - Form 1

cctv defects - 1

Enter # of each defect found on CCTV video:

	# of		
Cracked Joint	____	Corroded Pipe? (yes=1,no=0)	____
Offset Joint	____		
Open Joint	____		
Leaking Joint	____	Change In Pipe Size? (yes=1,no=0)	____
Circular Cracks	____		
Longitudinal Cracks	____		
Multiple Cracks	____	Cross Connection? (yes=1,no=2)	____
Dips in Line	____		
Mineral Deposits	____		
Root Growth	____		
Crushed Pipe	____		
Missing Pieces	____	Break in Service	____
Hole in Pipe	____	Leaking Service	____
Deformed Pipe	____	Protruding Service	____
Horizontal Misalignment	____	Abandon Service	____

User Input - Form 2

pipe material

Material Type: (select one)	PVC Clay Concrete Ductile Iron Cast Iron

User Input - Forms 3, 4, 5, 6 & 7

---

pipe diameter

Diameter (in.) ____

****

pipe length

Length (ft.) ____

****

pipe invert out

Upstream Pipe
Invert Out (ft.) ____

****

pipe invert in

Downstream Pipe
Invert In (ft.) ____

****

pipe depth

Avg. Depth (ft.) ____

User Input - Form 8

---

pipe location

Pipe Location: (select one)	Admirals Row
	Willoughby
	Camp Allen
	AFSC
	Ben Moreell
	Piers
	Main Roadway
	Secondary Roads
	Playground
	Open Field
	Intersection

User Input - Forms 9 & 10

capacity required

Capacity Required (gpm) ____

****

surface condition

Surface Type: (select one)		
	Grass	____
	Dirt	____
	Gravel	____
	Asphalt	____
	Concrete	____
	Reinf. Concrete	____