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CULVERT INFORMATION MANAGEMENT SYSTEM – DEMONSTRATION PROJECT

FINAL REPORT

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16. Abstract

The overall objective of the research was to develop a pilot scale Culvert Information Management System (CIMS) that will comply with both requirements stipulated by the Governmental Accounting Standards Board (GASB-34) and new federal storm water regulations. A framework for inspection and rehabilitation/replacement of corrugated steel culvert pipes (culverts) is developed, and this report will form the basis for the creation of a computerized CIMS. The justification of the development of the CIMS is based on recent GASB-34 requirements. The CIMS will serve as a vehicle for evaluating underground infrastructure assets, specifically culverts, and facilitate computing present worth and comparing present costs of preserving them. Benefits of the CIMS will include long-term savings that should accrue from adopting optimized preventive maintenance strategies.

The Condition States of culverts are used to express the extent of their deterioration. Different rehabilitation options are discussed and recommendations are made for deteriorated culverts. These options that will be incorporated into the CIMS, use survival probabilities based on the condition state of culverts. The survival probabilities for being in Condition States 1, 2, 3 or 4 are computed based on minimal field data. However, the CIMS requires additional field data for culverts or laboratory tests that mimic field conditions to enhance this capability.

The CIMS is capable of analyzing decisions to inspect, rehabilitate/replace or do nothing at both project and network levels. At the project level this is achieved by comparing inspection and/or rehabilitation/replacement costs with risks and costs associated with failure. At the network level, the associated costs are optimized to meet annual maintenance budget allocations by prioritizing culverts needing inspection and rehabilitation/replacement.

The CIMS consist of three major computer software components: databases, user interfaces, and a data administration module. Secondary components include an inlet/outlet structures module and a culvert segments module. The inlet/outlet structures module will store all the storm water data such as the quality/quantity of water and the receiving and discharge watersheds. Users will be able to retrieve culvert and inlet/outlet information and generate reports via location and road/milepost for condition state and assets needing immediate repair. The CIMS will also do the following operations:

- Maintain an up-to-date inventory of eligible infrastructure assets.
- Perform condition assessments of eligible infrastructure assets at least every three years, using a replicable basis of measurement and measurement scale.
- Summarize the results, noting any factors that may influence trends in the information reported.
- Estimate yearly the annual amount needed to maintain and preserve the eligible infrastructure assets at or above a prescribed level.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Culvert Pipes play an integral part in transportation infrastructure since they facilitate safe drainage. Typical diameters of culverts that are used range from 6-inches to several feet. The complexity and direct costs of their maintenance are increased with the increase in diameter. Indirect costs associated with maintenance, replacement, risk of failure, and highway closure and property damage due to flooding and litigations have also become significant. FHWA (1995) discusses operational and serviceability related issues pertaining to deterioration of the structure and its appurtenances, over time.

A loss of culvert integrity could result in temporary roadway closure and considerable rehabilitation/replacement costs or worse. In addition, the total collapse of a culvert could pose a major safety risk to motorists. Just such a catastrophic failure occurred on the New York State Thruway (I-88) near Unadilla, NY on June 28, 2006. The New York State Police photograph shown in Figure 1 illustrates the damage to I-88 resulting from a total culvert collapse. Two truck drivers were killed when their rigs fell into the washout caused by heavy rainfall. I-88 was closed in both directions from Schenectady to Syracuse. The washout of all four lanes and center median was a result of a failed 30-foot diameter culvert just beyond the Exit 10 interchange. (Albany Times-Union) Failures of this magnitude typically lead to catastrophic accidents, which may involve the loss of life and property, and can lead to losses of millions of dollars. Hence a culvert information system is necessary for timely maintenance of culverts and such system can only be developed if remaining service life values of culverts in the system are known (Meegoda, et al., 2005).

Figure 1. Collapse of New York State Thruway (I-88) due to culvert failure on June 28, 2006 (New York State Police Photo)

The service life of a culvert may differ from its design life, and it depends largely on the supporting soil, local environment, and corrosive and abrasive properties of the transported fluid and solids. Recognizing the effects of these factors on the deterioration of culverts and taking actions to maintain serviceability conditions can prolong its service life. This may prevent premature replacement of culverts and may also prevent costly culvert failures.

Currently, underground infrastructure asset accounting is based on a linear depreciation rate and not based on condition assessment of their present state. To ensure long-term durability of culverts and required compliance with federal accounting requirements, state departments of transportation (DOTs) are exploring ways to implement culvert inspection and management programs. This had been a requirement stipulated by the Governmental Accounting Standards Bureau, in the Basic Financial Statements and Management's Discussion and Analysis for State and Local Governments (i.e. GASB-34 Standard, 1999). GASB-34 requires the governing authorities to declare the present worth of infrastructure assets and to provide useful information on maintenance cost and future replacement cost. It also requires reporting of infrastructure assets as a depreciated cost, scheduled based on the historical cost or a discounted replacement cost. In the "GASB-34 Modified Approach" reporting the present cost of preserving eligible infrastructure is allowed in lieu of reporting depreciation or replacement costs.

State DOTs have found that funds made available to maintain infrastructure are insufficient in meeting GASB-34 requirements. Hence the need exists for adopting an optimal strategy that requires accurate information on the present state of infrastructure to be able to predict future performance. The modified approach lays out the requirements towards an efficient culvert maintenance and management system. It requires the state DOTs to:

- Maintain an up-to-date inventory of eligible infrastructure assets.
- Perform condition assessments of eligible infrastructure assets at least every three years.
- Summarize the results, noting any factors that may influence trends in the information
- Estimate the annual cost of maintenance for infrastructure assets, at or above the established condition level.
- Ensure that the result of the three most recent condition assessments meet or exceed the established condition level.
- Compare the estimated maintenance cost of infrastructure assets at or above the established condition level based on amounts spent during each of the past five reporting periods.

Many state and local agencies have yet to implement a culvert management plan based on the `Modified GASB Approach'. Collecting and interpreting data in order to assess the present Condition State with respect to deterioration requires accessibility to underground infrastructure, and the ability to perform a proper condition assessment. Hence, the above is a justification for implementing a preventive maintenance program, which incorporates user costs associated with culvert failures, such as due to flooding, roadway collapses and ensuing traffic delays and expensive repairs. In many cases indirect costs can easily exceed direct costs, and ignoring them can lead to less than optimal decisions. A properly developed Infrastructure Information Management System (IIMS) can effectively address the above.

IIMSs have been developed for pavement and bridges, and some of these systems incorporate maintenance policies (Abazai, et al., 2004, Aktan, et al., 1998, Arnoult, 1986, Beaton and. Stratfull, 1962). In many of these systems the Condition States of the infrastructure are estimated through visual inspection. Ellis et al., (1995) and Madanat and Ben-Akiva (1994), proposed models to account for partially observable infrastructure. Madanat and Ibrahim (1995) used a regression model based on Poisson's Distribution to estimate the transition probabilities between infrastructure Condition States.

Deterioration models described above are incremental models since they predict changes over time. Abazai et at (2004)., discussed an integrated pavement management system designed to provide pavement engineers with an effective decision-making tool for planning and scheduling of pavement maintenance and rehabilitation using an optimization process.

Information pertaining to degradation can be based on a theoretical analysis, obtained by experimental observations, or from expert information. Enright and Frangopol (1998) proposed a physics-based relationship to quantify degradation, while Lu et al., (1997), obtained a statistical distribution of time to failure based on field data. Liu and Frangopol, (2004), introduced a safety index to account for user costs, while Hassanain and Loov, (2003) proposed that user costs be included starting from the design stage. Tao et. al., (1995) introduced a Markov Decision Process model and Structure Reliability Theory for structural designs that included maintenance and management policies over its design life. Curtis and Molnar, (1997) described the development of a Municipal Infrastructure Management System (MIMS) model. However, it is observed that there is limited literature on infrastructure information management systems for underground infrastructure such as pipes and culverts. Micevski et al., (2002) presented a consistent Markov model for the structural deterioration of storm water pipe infrastructure. They concluded that both structural and serviceability conditions should be considered when determining a storm water pipe network strategy. However, the database has not been utilized to make management decisions. The following sections describe the framework needed to develop a culvert information management system (CIMS).

Culvert Information Management System

At present, New Jersey Department of Transportation (NJDOT) is exploring the development of a Transportation Asset Management System (TAMS) utilizing their Straight Line Diagrams, and the proposed CIMS will be an integral part of the TAMS. It currently includes following information pertaining to condition assessment obtained during culvert inspection/cleaning, along with a representative digital photographs. Currently, it is anticipated that the digital video files will be stored separately due to their size.

- Project data processing # or DP #
- Route and control section
- Video operator's name
- Inspector's name
- Inlet and Outlet Mile Post # and GPS location
- Standard route identification (SRI)
- Geographical description of all structures
- Depth of inlet and outlet structures
- Condition of inlet structures
- Date and time of video inspection
- Pipe material, diameter, thickness and length
- Length between pipe joints
- Direction of flow
- Pipe slope
- Pipe conditions and condition state
- Direction of video upstream/downstream

The above information and associated financial information will be used in making the required culverts management decisions. Culverts in the network should be inspected and Condition States should be known to make prudent management decisions.

Management of Culverts

In response to the GASB 34 provisions, NJDOT initiated a major research study with NJIT to investigate the deterioration of culverts. The overall objectives of this research are to investigate causes of the deterioration of culverts, then to develop a plan for implementing an effective, statewide, preventative maintenance program for culverts so that pipes can be repaired and rehabilitated before failure occurs, and to determine the best practice for using culverts in new construction. This report describes the initial results of this study, specifically, the results of a literature search; methods for inventorying, inspecting, and cleaning culverts; means of assessing the condition of culverts, estimating pipe deterioration rates, and predicting service life for pipes.

In addition, the research will investigate methodologies for determining the appropriate corrective action, i.e., to repair, rehabilitate or replace; study methods of record keeping and data storage; estimate the cost and recommend a preventative maintenance program for culverts and best practice for use of culverts in new construction. Consequently, design recommendations and guidelines will be formulated to develop a culvert management strategy.

Culvert Materials

There are different types of culvert materials in use today. They include the following: Log/Wood, Cut Stone, Slate, Cast Iron, Concrete, Plastic, Steel, Aluminum, Brick, Masonry and Clay pipes. The CIMS research has narrowed its research to these five types of material; Brick/Clay, Concrete, Iron, Corrugated Steel and Corrugated Aluminum. The reason is that the NJDOT is currently using these five material types, and they have been in use for a long time. Therefore, they are well studied. Please note that though plastic is a popular culvert material it is not used for roadway culverts in New jersey for safety reasons.

Concrete

Public health requirements for water and sewage treatment set the beginnings of the concrete pipe industry in the late 19th and early 20th centuries. Plants were established to manufacture pipe for sewers, transportation facilities, irrigation and drainage of agricultural land, and urban storm water drainage.

Sewage disposal methods did not improve until the early 1840s when the first modern sewer was built in Hamburg, Germany. It was modern in the sense that houses were connected to a sewer system. For the first time, sanitary sewers were separate from storm sewers. Paris officials had begun to design sewers at the start of the 19th century to protect its citizens from cholera. The cholera epidemics that ravaged England in 1854 led authorities there, to design and construct a sewer system in 1859.

Many of the early sewers in North America were built in small towns, and financed with local funds. Details of these early sewerage projects are generally unknown because of the lack of accurate records. The oldest recorded concrete pipe sanitary sewer installation was in 1842 at Mohawk, New York. The initial conception of engineered sewer systems in America has been credited to Julius W. Adams who designed the sewers in Brooklyn, New York in 1857. His designs were used as a model for years.

Brick/Clay

Brick/Clay pipes have been found in excavations dated as early as 4000 BCE. They were used in Mesopotamia, the Indus Valley civilization, the Minoan civilization, and of course the Roman Empire (which also used lead pipes). Modern-era pipes are made with a variety of materials. In the US, brick pipes are reported to have been in use as early as 1884 in Portland with lengths of up to 2000 miles. Please note that brick and clay culverts are found in older cities such as Newark and Camden.

Iron Pipes

Cast-iron pipe began to become available in the mid-1700s for municipal water service. The first large-scale use of cast-iron pipe for distribution of water occurred in 1664 at Versaille, France. The first cast-iron pipe manufactured in the United States was produced in a foundry in Weymouth, New Jersey, in the early 1800s. The city of Philadelphia began installing cast-iron pipe in its water distribution system circa 1804-1810. In fact, Philadelphia was the first American city to use cast-iron pipe exclusively -- due to its greater longevity and the fact that water pressure that could be maintained with it was higher than wood pipe could handle.

Corrugated Steel Pipe

Corrugated Steel Pipe, which was the first introduced to the construction industry in 1896, has had many revisions to the basic metal composition, corrugation patterns, and coatings since that date. In conjunction with the manufacturing developments, many State Highway Departments and various agency engineers have conducted numerous durability studies to determine the life expectancy of corrugated steel pipe.

Corrugated Aluminum Pipe

The origin of corrugated metal pipe can be traced to Crawfordsville, Ind. James Watson and Stanley Simpson came upon the design idea when using corrugated cardboard boxes for shipping. In 1896, they filed a patent for the manufacturing of corrugated metal pipe. By applying their idea to metal, they created an excellent alternative to the masonry, vitrified clay tile and sheet metal culverts used at the time. As a drainage structure, corrugated metal pipe offered a wide range of structural strength to withstand severe environmental conditions and burial depths. The Watson-Simpson patent was purchased in 1904 by a company that is known today as CONTECH Construction Products Inc. CONTECH is responsible for many corrugated metal pipe innovations. With more than 130 patents received and 13 patents pending, CONTECH's design engineers have helped establish numerous industry standards for pipe configurations, coatings and linings. In the 1950s, CONTECH had filled a patent to manufacture Aluminized Steel pipes in the United States of America. In this process, steel was hot-dipped in aluminum and the resultant corrugated aluminum-clad pipe can withstand highly corrosive environments.

Table 1 - Advantages and disadvantages for each material type

Material	Advantages	Disadvantages
Concrete	High strength/Durable/Fire resistance/Easily available/Water tightness/Wide range of diameters/High external loading	Weak in sulfate environments/Unlined concrete pipe is subject to scouring by wastewaters carrying grit and sand at high velocities/Requires careful installation to avoid cracking/Heavy
Brick/Clay	Resistant to Acids, Alkaline, Scouring and Erosion/Strong	Not readily available/Available only in large diameters/Not easy to install/Brittle/Joints are susceptible to chemical attack/Short length and numerous joints make it prone to infiltration and more costly to install
Iron Pipes	High strength/Ductile/Good corrosion resistance when coated	Heavy/Susceptible to corrosion from wastewaters containing acids, and from aggressive soils
Corrugated Steel	Fast and ease of installation/high strength to weight ratio/Strong/ Versatile/Cost-efficient	Susceptible to corrosion from wastewaters containing acids, and from aggressive soils
Corrugated Aluminum	Fast and ease of installation/high strength to weight ratio/Strong/ Versatile/High corrosion resistant/ Durable	Slightly costly/Not readily available

Table 2 - Expected design life for culvert materials (Sewer Manual, 2001)

Material	*Expected Design Life (years)*
Brick/Clay	150
Concrete	75
Iron Pipes	75
Corrugated Steel	30
Corrugated Aluminum	75

Table 1 provides a comparison in terms of advantages and disadvantages of each material type, and Table 2 provides the average expected design life of each material type.

Culvert Inspection and Inspection Frequency

The assessment of culverts is a difficult exercise because culverts are usually substructures, submerged, or placed in a remote location. Comprehensive and properly documented inspections need to be carried out to determine whether culverts require repair, rehabilitation, or replacement.

The previously mentioned collapse of New York State Thruway (I-88) due to culvert failure on June 28, 2006, and the failure of a culvert under the westbound lane of I-70 near east Vail, Colorado during high runoff on June 1, 2003, suggested the need for regular inspection of highway culverts. The culvert failure in Colorado caused the shutdown of 25-mile stretch of I-70 and 54 mile detour over two mountain passes for several weeks. Culverts should be inspected on a routine basis to ensure that they are functioning properly. Presently, there is no standardized or consistent methodology to inventory, inspect, and evaluate culverts in the field. Inspection of culverts is very important to ensure a successful pipe inspection program. Established standard guidelines must be put into place under which all inspectors should function so that data will be consistently collected. It is also necessary to schedule inspections on a regular basis.

Visual inspection is the most common method of culvert inspection. However, some departments of transportation and road authorities also make use of video cameras. Typically, visual inspection lacks consistency because multiple inspectors perform them. MnDOT (Ulteig Engineers, (2001)) and City of Waterloo (Gallivan, 2002) utilized photographs and video cameras to enhance assessment. Other agencies are also considering purchasing video cameras after seeing benefits that were being derived. Other options include digital video and still photos.

The Federal Highway Administration (FHWA, 1995) developed a comprehensive Culvert Inspection Manual that describes in detail inspection procedures, guidelines and inspection frequency. FHWA (1995) required that inspections be performed once in every 3 years (Arnoult, 1986). NCHRP Synthesis 303 on Assessment and Rehabilitation of Existing Culverts also documents the following methods for inventorying, inspecting, and cleaning culverts:

1. There is a need to establish a standard set of guidelines, under which all inspectors will inspect and consistently collect data.
2. NYSDOT and Connecticut DOT have comprehensive culvert inventory and inspection manuals that describe their culvert management program.
3. Some agencies cleanse their large diameter culverts between 2 – 3 year intervals.
4. There is need for a regular inspection schedule, similar to that provided in the National Bridge Inspection Standard (NBIS, 2001). However, regular cycles are not followed by transportation agencies.

Major culverts should be scheduled for inspection at least every three years, but if the conditions are mild where the structure is located, inspection may be carried out every four years with FHWA (1995) approval. Although FHWA (1995) recommends that inspections be performed every 3 years, our research led us to conclude that if a comprehensive inspection program is adopted, the frequency may vary from 1 to 10 years based on the hydraulics, location and importance of culverts. Some critical culverts, e.g., those crossing major highways and connected to upstream or downstream hydraulic structures that are not owned and maintained by DOTs may need to be inspected more frequently, even annually. While others, e.g., small diameter new culverts running along the highways that are not in highly erodible or corrosive environments may be inspected with much less frequency.

Table 3 - Proposed culvert inspection frequency

Rating Level	I	II	III
Inspection Frequency:	10 yrs	3 yrs	1 yr
BASIS FOR TIME INTERVAL	Self-cleaning design (10-year flood) for Small Diameter culverts	FHWA (1995)Guidelines	Reported problems
BASIS FOR LEVEL	Free of corrosion and debris	Evidence of corrosion and/or debris	Reported clogging or collapse
Physiological Features:			
SEDIMENT	Low Abrasion- Minor bedloads of sand and gravel $V < 1.5$ m/s	Moderate Abrasion- Bedloads of sand and gravel 1.5 m/s $< V < 5$ m/s	Severe Abrasion- Heavy bedloads of gravel and rock $V > 5$ m/s
pH	$5.8 < pH < 8.0$	$5.0 < pH < 5.8$	$pH < 5.0$
Location:			
Corrosion/Erosion – (Conductivity Maps & Historical Data)	Low or none	Medium	High
Pipe Age as % of Design Life	30%	50%	100%

NJIT proposed a new inspection frequency for culverts in New Jersey that is shown in Table 3. The table categorizes culverts into three categories based on the following factors, i.e., corrosion and erosion, bed load, pH, and culvert size, age and importance. Culverts falling into Category I are considered to be working fine, while those in category III require urgent attention. Corrosion is a major cause of deterioration of culverts; hence culverts exhibiting excessive corrosion require urgent attention. Acidity of the environment in which culverts are located also plays a dominant role in the deterioration process of culverts; hence culverts in high acidity environments deteriorate at a faster rate and hence need to be inspected more frequently. Culverts, like other infrastructure, generally deteriorate at a faster rate with age, and hence require more frequent inspections with increasing pipe age, i.e., as they approach their design service life.

Based on the selection criterion in Table 3, one needs to select the most stringent inspection schedule. For example, all large diameter culverts crossing major highways should be by default in category II or III. We were unable to express the bed load, which is a measure of culvert erosion, in terms of a more tangible parameter. Hence, bed load should be selected after visiting the location of culverts and examining the surrounding soil. If it is gravelly select a high value, sandy medium value and silt or clay select the lowest value. A computer program was developed at NJIT to select the inspection frequency of a given culvert based on the criteria shown in Table 3.

Culvert Cleaning

There are various equipment and methods commercially available today for cleaning culverts. The type of equipment and method to be used depends upon the characteristics of the material to be removed and the degree of movement and versatility required. Table 4 provides a list of available methods for culvert cleaning with the advantages and disadvantages of each method. Selection may be based on video inspection of a problematic section or the entire system. The video inspection systems can also identify pipe features that are important in the selection cleaning methods, e.g., the location of offset joints, broken pipes, protruding laterals, off grade pipes, leaking joints, recessed taps, cracked pipes, blockages, corrosion, root infiltration, obstructions and collapsed pipes. Plus, these systems can inspect clean-outs, drain lines, service laterals; vent stacks, floor drains, and water lines. The aim is to free the culvert from debris and regain normal flow of water.

Table 4 - Pipe cleaning methods

CLEANING METHOD	ADVANTAGES	DISADVANTAGES
Vacuum Pump	Capable of removing stones, bricks, leaves, and sediment deposits	Limited to working depth of 6m
Water Jet Spray	Effective in cleaning pipes that require high pressure and general cleaning	Cannot be used to clean culverts due to the damage to protective coatings.
Buckle Line	Easily available and can be used for general cleaning and sediments removal	Limited to large pipes of over 48 inches diameter or width.
Compressed Air Jet	Effective in removing debris from vertical walls	Normal working depth limited to 20m (75ft).
Fire Hose Flushing	Effective in removing light materials from the wall and for general removal of light materials	Limited to light to light sediments and materials
Sewer Jet Flushes	Effective in cleaning area with light grease problem, sand and gravel infiltration and general cleaning.	Much more expensive than other methods.

Condition Assessment

Once culverts are in place and operational, they are exposed to internal and external deterioration agents like acids, debris, aging, alkaline, abrasion, erosion and moving traffic. The longer these agents are allowed to act on the culverts, the more deteriorated they become. Condition assessment as a process has been summarized in the following steps:

1. Measure the extent of damage/deterioration.
2. Determine the effect of that damage/deterioration on the condition of facility.
3. Set the scale of parameters that describe the condition of the facility as a whole.
4. Compare the existing damage/deterioration with previous records of condition assessment.

For example, AASHTO specified a simple condition rating process that describes three to five classes of conditions. The condition states were designed to be consistent and repeatable if used by certified inspectors. The sewer industry has developed a five condition state system and are offering training courses to certify inspectors, and hence it is a good system to be adopted for culverts. The proposed condition states for culverts are defined below based on the Sewer Manual, 2001:

Condition State 1: (Excellent)

There is no evidence of active corrosion of the structure with any measurable section losses. This state refers to pipe condition where there is no visible deterioration. The time frame a pipe is in this state depends largely on the applied pipe coatings. Since there are no visible signs of pipe deterioration after pipe cleaning and inspection, no action is recommended.

Condition State 2: (Good)

Minimal likelihood of collapse in the short term, but potential for further deterioration. The average sectional loss is less than or equal to 10% of thickness. Culvert repair guidelines of the FHWA (1995) and state DOTs have not highlighted the importance of cleaning and painting at such an early stage of its design life.

Condition State 3: (Fair)

Collapse unlikely in near future, but further deterioration likely, including swelling with surface pitting. Section loss due to active corrosion is measurable, but does not affect the strength or serviceability of the structure. The average section loss is between 10 to 30% of thickness. The deteriorated culvert pipes can be rehabilitated provided that the deteriorated pipe could provide the necessary structural strength for the remaining life period. This however may not be a cost effective option in the long term.

Condition State 4: (Poor)

Corrosion is advanced, with collapse likely in the foreseeable future. The culvert exhibits heavy section loss warranting analysis to ascertain the impact on the ultimate strength and/or serviceability of the structure. The average section loss is greater than 30% of section thickness. Under this condition state in-situ pipe rehabilitation techniques are considered to be promising.

Condition State 5: (Very Poor)

Collapsed or collapse imminent. At this point, the pipe cannot be repaired or rehabilitated. The only solution is replacing with a new culvert/pipe by either excavation or trenchless technology methods. Some of the trenchless technologies include pipe sliplining and pipe bursting.

Relating Conditions States of Culverts to Remaining Service Life

Figure 2 shows the variation of condition classification with percentage of effective life elapsed for an existing infrastructure. This graph characterizes the annual asset repair and replacement needs for existing infrastructure, such as a particular pipe network, or even the set of all utility assets. It is based on when the assets (for example, pipes) were installed, and how long they are expected to last before it is economically efficient to replace them. Estimates of refurbishment and replacement cost have also been included (AWWA 2001). The five level condition states proposed above (Sewer Manual, 2001) correspond to the condition classifications shown in Figure 2.

The actual failure time of a culvert depends on the culvert materials. For instance on average corrugated steel culvert would reach condition state 5 in thirty years while a cast Iron would require 75 years under similar environment. There are many different types of culvert materials that are still in use today. They include the following: Timber/Wood, Cut Stone, Slate, Cast Iron, Concrete, Plastic, Steel, Aluminum, Brick, Masonry and Clay pipes. Since estimating the remaining service life of a particular culvert is dependent upon its current condition state and also on the material type, this list , as previously mentioned, has been narrowed based on our literature search and NJDOT usage to the following five most prevalent material types; Brick/Clay, Concrete, Cast Iron, Corrugated Steel and Corrugated Aluminum. Table 1 provided a comparison in terms of advantages and disadvantages of each material type, and Table 2 provided the average expected service life of each material type.

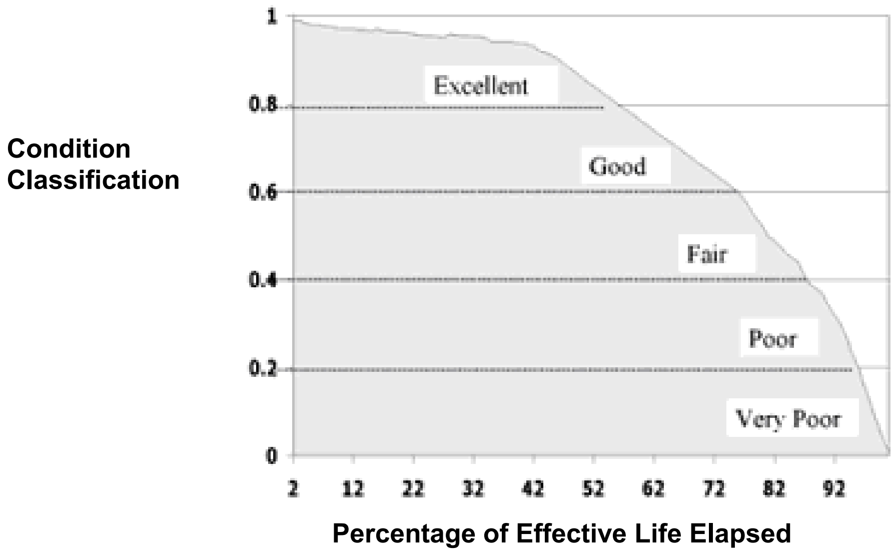


Figure 2. Variation of condition state with the elapsed life (WBI 2006)

In order to estimate the remaining service life of culverts one must develop curves for the variation of condition state with the elapsed time similar to the one shown in Figure 2 for each material type. These curves are termed "Nessie Curves" named after the Loch Ness Monster because of their shape, and so much of it lies beneath the surface. It starts out with a relatively flat slope and has an increasingly negative slope with time. In essence, it overlays the type of products that you have both in ground, the type of material, the type of soil, the year of construction, what actually flows and may even include who constructed it (Regulatory Commission of Alaska, 2007 and Mills, 2002).

The Nessie curve enables a utility to understand the scope and nature of the future infrastructure or asset cost requirements. The history of a pipe network installation by water and wastewater utilities in most cities in the industrialized world means that these curves of estimated future costs are seen to rise in a wave shape over the next half-century. (Etnier, et. al., 2005)

With the help of Nessie Curves, culvert rehabilitation expenditures over time can be projected into the future. It helps evaluate when a utility needs to replace its assets and optimize the cost of replacement over time (AWWA, 2001). It gives you an idea of when specific segments of pipe on a segment by segment basis, will require replacement. It also allows you to look at your major infrastructure. (Regulatory Commission of Alaska, 2007)

The Australian utilities equip themselves with a what-if framework for investigating replacement strategies and financing needs interactively with their governing boards. The Nessie Curve is the key that enables them to predict the total cash flows needed for repair, rehabilitation, and replacement in order to sustain the service capacity of their assets. Process-benchmarking studies are supposed to provide breakthrough opportunities for performance improvement by finding best practice ideas and adopting them. Discovering the Nessie Curve, and the means for quickly developing and using it, is a positive step for North American utilities (Cromwell, et. al., 2004). Nessie Curves are developed from historical data, the elapse time and condition state. However, such data are scarce, especially for culverts, as culvert inspection was a recent phenomenon. The yearly maintenance and rehabilitation work to be carried out in the current year is based on condition state of the culvert during the previous year. Meegoda et al., (2004) predicted the survival probability of a culvert in urban environments with service time using data from an American Society for Testing and Materials (ASTM) study. However, such material information is not available for other four types of materials. Hence, this research attempted to develop such curves based on theoretical analysis with limited field data. However, the authors emphasize on the need to generate such curves from historical field data and from accelerated laboratory tests (i.e. mimicking field conditions), during actual implementation.

Reliability Analysis

The reliability of the culvert is the probability that it will operate for a specific period of time, e.g., its design life, under its design conditions without a failure. The Weibull distribution is widely used in reliability modeling since other distributions, e.g., exponential, Rayleigh, and normal are special cases of the Weibull distribution. Its time to failure distribution f(t) is given as

$$f(t) = (\gamma/\theta)t^{\gamma-1}e^{(-t^{\gamma})/\theta} \tag{1}$$

Where θ and γ are positive and are referred to as the characteristic life and the shape parameters of the distribution respectively.

The hazard rate (or failure rate) function h(t) for the Weibull distribution is given by

$$h(t) = (\gamma/\theta)t^{\gamma-1} \tag{2}$$

When γ>1, the hazard rate is a monotonically increasing function with no upper bound that describes the "wear-out" region i.e., higher condition states with little remaining service life. The hazard rate becomes constant for γ = 1, which is typical for the design life. When γ <1, the hazard rate is a monotonically decreasing function that describes the early failure-rate region. These failures are typically attributed to manufacturing defects or improper installation and are not considered in this analysis.

The reliability R(t) for the Weibull distribution is given by

$$R(t) = e^{(-t^{\gamma})/\theta} \tag{3}$$

And the cumulative distribution function of failure F(t), which is the compliment of R(t) is given by

$$F(t) = 1 - R(t) = 1 - e^{(-t^{\gamma})/\theta} \tag{4}$$

The flexibility of the Weibull model enables it to describe the failure rate of many failure data in practice, and we will apply this approach to estimate the remaining service life of several types of culverts. (Elsayed, 1996 and Burn, 2001)

The expected design life for each material t_d is given in Table 2. It can be shown that the characteristic life parameter, θ is equal to $(t_d)^{\gamma}/\ln(2)$. Hence, equation 3 can be rearranged as shown below.

$$R(t) = e^{[-(t/t_d)^{\gamma}\ln(2)]} \tag{5}$$

In this research it is assumed that a culvert has failed when its reliability has decreased to 5%, and its age has reached 150% of its expected design life value. Furthermore, since the characteristic life parameter θ is assumed to be equal to $(t_d)^{\gamma}/\ln(2)$, then the shape parameter γ can be back calculated to be equal to 3.6. The mathematical derivation for the above will be presented in a theoretical journal appropriate for such analysis, while it is used in this manuscript to illustrate the basis for the remaining service life prediction based on condition state evaluated from culvert inspection.

Figure 3 shows the predicted variation of condition classification with normalized life (t/t_d) based on equation 5 with the actual but limited culvert data. Please note that a condition classification value of 0.5 was obtained when the service life was equal to the expected design life, or t/t_d =1. Out of over one hundred NJDOT video inspection data files, five representative culverts representing the five material types considered were selected, and the details of those culverts including material type, years in service and condition classification are listed in Table 5. Figure 3 also plots this information along with the theoretical predictions. The corrugated metal pipe data falls on the theoretical curve, which is no surprise since we have had over five years of research investigating the performance of corrugated steel culvert pipes. Based on Figure 3 it can be concluded that behavior of other culvert materials could be reasonably predicted from the above theory.

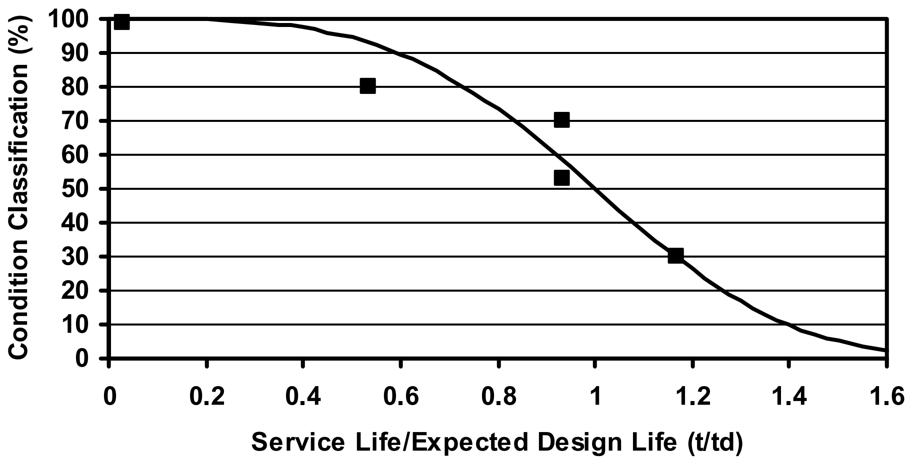


Figure 3. Variation of condition classification with the ratio of service life to expected design life

Table 5 - Culvert inspection data

Culvert Material	*Years in Service*[1]	*Condition Classification (%)*[2]
Corrugated Steel	35	30
Corrugated Aluminum	2	99
Cast Iron	70	70
Reinforced Concrete	70	60
Clay	80	80

[1]Obtained from NJDOT Archived Contract Documents
[2]Obtained from NJDOT Inspection Videos

REMAINING VALUE OF CULVERTS

This methodology can be used to predict the remaining service life of culverts, and hence their remaining value, once they are inspected, and their condition state has been determined. For instance, let us assume that a corrugated steel culvert is inspected and found to be in condition state 3. Hence, the condition classification would be 40%-60%. Then using Figure 3 or equation 5, the values of (t/t_d) for 40% and 60% condition classification would be 1.075 and 0.925 respectively. Based on Table 2 corrugated steel culverts have an expected design life of 30 years. Therefore, the average remaining service life of this culvert would be 15 years. Hence, if it costs $1M to construct this culvert, the present worth of this culvert would be approximately $500,000.00. Please note that with the above prediction of the remaining service life, the culvert has a service life of 15 years beyond the design life, and this is due to the factor of safety associated with the design. The above remaining value calculation can be drastically simplified by computing the value based on survival probability. That is the remaining value would be survival probability multiplied by the value, which also gives the same result. This information would be used in the Culvert Information Management System, which is currently being developed for NJDOT to facilitate project and network level decisions for maintenance planning and budget allocation.

Relating Condition States of Culverts for Rehabilitation and Replacement
Culverts are factory-coated with metal and non-metals that act as a corrosion barrier, a sacrificial layer against abrasion, or a protective film against chemical effluents. Coatings are used singularly or in a combination of layers to enhance the service life when serious corrosion or abrasion problems exist (Meegoda and Juliano, (2005)). The deterioration of a newly installed culverts sets in when the factory applied coating is damaged. This results in the progressive removal of the asphalt and/or galvanized layer, exposing the bare steel surface to corrosion (DiBiaso M, (2000)). The subsequent loss of parent metal may lead to perforation of the pipe and eventual structural failure. The condition state of the culverts identifies the degree of deterioration and distinct changes in structural serviceability. As culverts deteriorate, its Condition State is increased.

The use of appropriate coating materials and thicknesses are key factors in determining the durability of culverts. Acidic environments and exposure to salt water exacerbate corrosion in steel culverts. Furthermore, the chemical and physical characteristics of the surrounding soil and effluents containing various chemicals, chlorides and other dissolved salts that come into contact with the pipe may accelerate galvanic corrosion.

The rehabilitation option that is appropriate for a particular culvert depends on its state of deterioration. The FHWA (1995) relates structural strength and serviceability to deterioration of metal culverts. Inadequate flow capacity, corrosion and abrasion, sedimentation and blockage by debris, separation and/or drop-off of sections of modular culverts and inadequate length are identified as serviceability related. The undermining and loss of structural support, loss of culvert inverts due to corrosion or abrasion, over-deflection and shape deformation are listed as strength related. The main conditions that affect culverts are identified as invert deterioration, shape distortion, soil migration, corrosion, and abrasion. Observations and measurements done to determine shape distortions enable one to identify whether deterioration has affected the structural integrity of the pipe. The decision to rehabilitate or replace a culvert depends mainly on the degree of deterioration, and whether the structural integrity of the pipe has been compromised.

<u>Painting</u>

Cleaning and painting is an important measure in impeding corrosion and towards extending the service life of the culvert pipe. Pipe coatings in general are considered to add five years to the expected life and are found ineffective under abrasive and high flow conditions. In such situations Caltrans (2003) recommends the use of alternate invert materials or techniques.

Metal Coatings
Some culverts are factory-coated with metallic and non-metallic protective layers. They act either as a corrosion barrier covering the entire periphery of the pipe, as a sacrificial layer of abrasive resistant material (generally concentrated in the invert of the pipe), or to protect pipe from chemical effluents.

They can be used singularly or in a combination of layers to enhance the service life of the metal culvert. MoDOT design specification explains the procedure to carry out field repairs.

Bituminous Coatings and Paving

Bituminous coatings are the most common materials used to protect corrugated steel and aluminum pipe against corrosion. Corrugated pipes are factory coated in the interior and exterior surfaces with a minimum thickness of 0.05inches; lined or paved to a minimum thickness of 1/8 inch above the crest of corrugation to provide a smooth interior surface. Bituminous coatings and paving are said to enhance the service life of culverts by 20 to 25 years and bituminous coatings alone adds about 8 years to service life (USACE, 1998). However, for cold regions such as Northwestern New Jersey with many freeze/thaw cycles per year, bituminous coating may be not applicable.

This procedure can also increase the resistance of metal pipe to acidic conditions if the coating is properly applied and it remains in place. Careful handling during transportation, storage, and installation is required to avoid damage to the coating. Bituminous coatings are susceptible to damage by abrasion. Field repairs should be made when bare metal has been exposed. Aramid fibers may be embedded in the zinc coating to improve the adherence to metallic-coated bituminous material pipe. It should be noted that the durability of bituminous coatings is dependent on strict adherence by the fabricator to proper coating procedures (FHWA 1995).

Polymer Coatings

Plain plastic coatings are applied directly to the metal or to other surface coatings. Several types of polymer coatings are available that provide corrosion resistance under extreme environments such as in the presence of chemical effluents, salts, acids and bases. Culverts are also coated with polymer concrete, which is a mixture of plastic and aggregate. There have also been recent developments for coating metal culverts with fiberglass (short glass fibers held in a resin matrix). Polymer coatings are said to add approximately 10 years of service life to corrugated steel pipes (USACE, 1998). However, the 10 mil thick PVC and polyolefin plastic coatings that may be used to coat metal culverts do not provide increased resistance to abrasion, although polyethylene will to some extent (FHWA 1995). NYSDOT (1996) finds certain types of 18-gage polymer coated steel pipe not conforming to Highway Design Manual criteria for open or closed drainage.

Invert Paving

Culvert pipe inverts are paved with asphalt cement, asphalt concrete, cement mortar or concrete. Concrete of good quality is resistant to many corrosive agents. When the effluent has a pH of 5.0 or less, protective measures are generally required. One problem with using this type of coating is getting a good bond or connection between the metal pipe and the mortar or concrete lining (FHWA 1995). Caltrans (2003) discusses invert paving with reinforced concrete as an effective way to rehabilitate corroded and severely deteriorated inverts. It finds that Class 3 or minor concrete or shotcrete sufficient for most cases where abrasion is not present. Harder aggregate and high strength concrete is recommended for cases where abrasion is present. A paving thickness of 75-150 mm is recommended based on the abrasiveness of the site; paving limits typically varying from 90 to 120 degrees for the internal angle. It recommends that steel reinforcement be properly anchored to resist the circumferential thrust loads. A detailed description of procedures is given in the FHWA (1995). Invert paving is used for pipe sizes where human entry is possible. For large diameter pipes, Caltrans (2003) recommends reconstructing the invert with steel plates.

Slip Lining

Slip lining involves sliding a new culvert inside an existing distressed culvert and is an alternative to total replacement. This method is much faster to complete than a remove and replace option, and often will yield a significant extension of service life at less cost than complete replacement, particularly, where there are deep fills or where trenching would cause extensive traffic disruptions (Caltrans, 2003).

The selection of a slip-liner type depends largely on the available structural strength of the deteriorated culvert pipe. A rigid liner is required when the extent of deterioration has progressed beyond a point where it cannot support soil pressure. This requires grouting of voids between the newly placed liner and the deteriorated pipe section. For metal culvert pipes where the level of deterioration has not affected the structural strength, both flexible and rigid types can be used.

When a slip-liner is installed, the hydraulic capacity of the culvert is altered. Selecting the size (i.e. the diameter) of the slip-liner depends on the available annular space to slide the liner and the surface roughness (i.e. Manning's n). The clearance between the deteriorated culvert pipe and the liner is grouted. In large culverts, selecting a liner with a smaller cross section may reduce the hydraulic capacity, thus change its hydraulic characteristics. In such situations, the headwalls and wing-walls should be designed and installed to enhance flow. This may be supplemented by the provision of temporary water storage at the inlet. The adequacy of outfall protection should be assessed since a higher discharge velocity is anticipated (FHWA, 1995).

Selection of the appropriate liner material should also consider the reasons for failure and mode of failure of the existing pipe. The choice of material for culvert liners depends on the field situation and physical needs of the installation, which includes handling and working space during installation, cost of construction and maintenance and the added service life. During installation of long and heavy slip-liners in corrugated metal pipes, often a large pressure is required to push the liners in to place. The difficulty increases with the roughness of the existing surface, and the type of exterior on the liner. Corrugated or ribbed liners will be the most difficult to insert, particularly if the existing culvert is also corrugated, corroded, and/or distorted (Caltrans, 2003).

Pre-cast Concrete Liners
A wide range of precast concrete shapes may be used to slipline culverts. One particular advantage of using precast concrete sections is that the sections are shorter in length than corrugated metal sections, and they may (in some ways) be handled somewhat easier. They may also be connected inside of the culvert, which minimizes the amount of working space that is needed outside of the culvert. They are frequently pulled into the culvert by using a pulley system that is attached to a strong back frame that spans one end of the existing culvert (FHWA , 1995).

Plastic Pipe Liners
A wide range of polyethylene, high density polyethylene and polyvinyl chloride (PVC) plastic pipes are available for lining culverts. Some of them have a corrugated outer surface or corrugations on both the inner and outer surfaces and others are smooth on the inside or on both sides. Others are folded for insertion and then expanded into shape with hot water, such as Nu-Pipe and U-Liner. Plastic pipe may be connected in several ways, but the most common are either by snapping them together or by fusion bonding them together. Normally sections of plastic pipe are connected together prior to their installation in a culvert. The Pipe Liners Incorporated system is manufactured in a circle. It is deformed to a U-shaped while it is still hot and, at the site, is expanded with steam after insertion (FHWA 1995).

Corrugated Metal Pipes as Liners

Many sizes of corrugated metal pipe (CMP), pipe arch and structural plate products are available. In general the pipe and pipe arch shapes must be prefabricated to the desired length or assembled by connecting them together at the jobsite. If multiple sections are needed, they may be connected together outside of the culvert and pulled or pushed into the existing structure. As an alternative if conditions permit, individual sections may be pulled through and assembled inside the existing culvert using tabs for alignment and grout to hold position. If structural plate pipe is used, the outside dimensions of the liner will have to be sufficiently smaller than the existing culvert so that workmen may handle fastening the bolts from both the inside and the outside. Clips can also be used so that the bolts can be tightened from the outside. A Spiral Rib (internal rib) CMP is available that has a low Manning's "n" factor, that minimizes the reduction in flow capacity (FHWA,1995).

Fiberglass Reinforced Cement (FRC) Liners

Fiberglass reinforced cement (FRC) liners are prefabricated thin panels designed for large diameter (1050 mm and larger) and odd shaped pipes. After the existing pipeline is thoroughly cleaned and dewatered the segments are provided in 1.2 m to 2.4 m (4 to 8 foot) lengths, which overlap at each end. The segment ends may be pre-drilled to accommodate screws or impact nails. The segmented rings are anchored on spacers and, upon final assembly, and the annulus is cement grouted. Laterals are cut in and grouted. This method provides flexibility to be made specially to fit any portion (e.g., invert only), shape or size of host pipe and to accommodate variations in grade, slopes, cross-sections and deterioration. The linings are not designed to support earth loads, therefore, the host pipe must be structurally sound. Although the segmented sections are lightweight and easy to handle, the installation is labor intensive and slow. The FRC liners are normally 10mm (three eighth inches) thick, but can vary. They are composed of Portland cement, fine sand and chopped, fiberglass rovings. They have high mechanical and impact strengths and also a high strength to weight ratio. FRC is more abrasion resistant than the concrete mix used in standard reinforced concrete pipe (RCP), however, their thickness is significantly less than the cover over the reinforcing steel in RCP (Caltrans, 2003).

Fiberglass Reinforced Plastic (FRP) Liners and Pipes

There are basically two types of fiberglass pipe that can be used to slipline culverts. However, they are generally more expensive than the plain unreinforced plastic pipe, and they are more routinely used to line pipelines. The largest, and strongest, of such pipe is filament wound with glass fibers in a polyester resin. The connections of fiberglass pipe include O-ring seals, with one being used for low pressure applications and two being used for high pressure applications. The other type of pipe is made with a combination of glass fibers and a sand-resin mixture, which produces a strong, but somewhat heavier and less expensive pipe (FHWA 1995).

New and rehabilitated sewer and drainage pipes are no longer limited to relatively small diameter FRP slip-lining methods. The in-situ epoxy resin relining process for cast iron, steel, ductile and asbestos cement pipes are a proven process for the protection of pipelines against internal corrosion. The acceptance of the process by the industry coupled with the awareness of the problems associated with corrosion of pipelines has led to an increasing demand for non-structural lining techniques (FHWA, 1995).

Fiberglass reinforced plastic (FRP) liners are similar in most respects to FRC liners. However, they are lighter weight and more resistant to chemical attack (e.g. sulfate), and therefore provide a better corrosion barrier (when used to line steel pipes) than FRC liners. They are also highly abrasion resistant with negligible absorption and permeability. The FRP liners are normally 13 mm (half inch) thick, but can vary. They are composed of thermosetting plastic resin (polyester or vinylester) and chopped, fiberglass rovings and mostly constructed with the same materials that are used to make fiber-reinforced polymer concrete. A sand free inner surface made of pure resin is provided for resistance to chemical attack and abrasion resistance. The fiberglass inner surface has a finish that is compatible with the type of resin employed. The outer surface is treated with bonded inert sand aggregate to enhance the adhesion to the annular space grout (Caltrans, 2003).

In-Situ Cured Liners

Cement-Mortar Lining

Cement-Mortar lining can be used in corrugated metal pipes where the structural strength is provided by the host pipe. In most cases it is required to pressure grout the voids around the pipe prior to placing the mortar lining. This technique could be used for metal pipes with diameters ranging from 300 mm to 7 m (Caltrans, 2003).

Typically, two passes are made resulting in a 13 mm minimum thickness over the leading edges of the corrugation pattern. Any grade (steepness) of pipe can be lined by this method and most bends do not present a problem. A polypropylene fiber mesh reinforcement additive will provide improvements in the strain capacity, toughness, impact resistance, and crack control. The mortar is made of one part cement, to one part sand. As with other liners, the pipes must first be thoroughly cleaned and dried. For diameters between 300 and 600 mm, the cement mortar is applied by a robot. The maximum recommended length of small-diameter pipe that can be lined using this method is approximately 200 m. Although this method will line larger diameter pipes, 600 to 3600 mm, it is mostly appropriate for non-human entry pipes (Caltrans, 2003).

Cement mortar lining provides a relatively smooth interior surface layer, which spans joints and repairs damaged or corroded inverts. Although the liner fills voids under eroded inverts and open joints between segments of a culvert, failures to bond to the existing culvert have been observed. This results in cracking, and hence looses its functionality. The likelihood of problems will depend upon many factors including: the types and degrees of distress, the choice of materials and methods, and the quality of workmanship. The cement mortar lining may be applied with mechanized equipment or pneumatically by the shotcrete technique. Both methods use a cement mortar that is quite dry (it has a very low water/cement ratio) so that it will remain on vertical and overhead surfaces without sagging or sloughing. The dry mix type of shotcrete is called "gunite." The mechanized process involves applying a layer of cement mortar against the inside periphery of the pipe with equipment that has either a rotating spray head or rotating trowels. The gunite method involves a workman spraying the mortar against the inside surface with compressed air and then finishing the surface by hand. There is a minimum size for using the gunite method, which is in the range of 5 foot diameter (FHWA, 1995).

Cured In-Place Liners

Cured in place (CIP) liners describe class of lining techniques whereby a polymeric lining is directly cast against a host pipe. The tube is then inverted or winched into the host pipe and then held under pressure against the host pipe by compressed air or water. The tube is then cured by ambient temperature, hot water, steam or ultraviolet light (INPIPE™), to form a composite lining. INPIPE™ uses a thermosetting resin, which is impregnated at the optimum temperature into a flexible tube of multiple layered glass fiber reinforcement with internal and external protective foils (Persson, 2001)

Certain CIP liner types have a thermosetting polyester resin-impregnated polyester felt tube with an interior surface coated with a layer of polyurethane that provide corrosion and abrasion resistance, and some reduction in roughness for increased hydraulic efficiency. These are cured in place by heating and recirculation of water that is used in the inversion of the polyester felt tube.

CIP liners are particularly suited for aggressive chemical environments. The continuous lining eliminates problems due to both exfiltration and infiltration of water that may have been passing through the walls and joints of the existing culvert. Since the liners do not provide the structural strength, the deteriorated corrugated metal pipe has to be remedied to provide the soil-structure interaction. CIP liners bridge all joints including open or displaced joints, and irregularities present in the inner surface, and conform to the shape of the barrel along the trace. They are made to fit the exact diameter, shape and length, pre-impregnated with the thermosetting polyester and polyurethane resins and shipped to the jobsite in a refrigerated truck or impregnated at the jobsite. The latter method is frequently used when the culvert is long and over 48 inches in diameter, since the weight of the resin-saturated liner is difficult to handle in its uncured state (FHWA, 1995).

In-Situ Pipe Replacement

Pipe Splitting

Pipe splitting is a technique used to split open existing ductile pipes and pull a new pipe in to replace the deteriorated one. The system uses a splitter, which cuts the existing pipe along one line on the bottom and opens it out, rather than fracturing it. The splitter is pulled through the existing pipe by either a wire rope or steel rods. It consists of one or more of three parts: (1) a pair of rotary slitter wheels, which make the first cut, (2) a hardened sail blade on the underside of the splitter, which follows, and (3) an expander, whose conical shape and off-centered alignment force the split pipe to expand and unwrap.

Pipe Eating

Pipe eating is a modified micro-tunneling system specially adapted for pipe replacement. The existing defective pipeline is crushed and removed through the new pipeline by the circulating slurry system. A new pipe is simultaneously installed by jacking it behind the micro-tunneling machine. The new pipe may follow the line of the old pipe on the entire length, or may cross the elevation of the old pipe on a limited segment only. The system is remotely controlled and guided with a surveyed laser line from the drive pit, and prepared to "eat" whatever is in the way, the old pipe or the ground only

Pipe Reaming

Pipe reaming is a modified back reaming method used in directional drilling, which is specially adapted for pipe replacement. First, the pilot drill string is inserted through the existing pipe. Next, a specially designed reaming tool is attached to the drill string and pulled back through the pipe, while simultaneously installing the new pipe. The reamer has cutting teeth, which grind and pulverize the existing pipe through a “cut and flow” process, rather than a compaction. The pipe fragments and the excess material from upsizing are carried with the drilling fluid to manholes or reception pits, and retrieved with a vacuum truck or slurry pump for disposal.

Slip Lining With Polymer Pipe With the Necessary Structural Strength

The availability of polymer based pipes, with the necessary structural strength, have made it a permanent option for replacement of culverts. Although these pipes have smaller diameters, their enhanced hydraulic characteristics and their resistance to corrosive environments, have made their use more attractive.

Pipe Bursting

Pipe bursting and related techniques are well-established methods for trenchless replacement of worn out and undersized gas, water or sewer pipelines. They can offer significant potential savings and drastically reduced surface disruption to public and private utility owners under favorable conditions. The methods result in an existing pipe being replaced size-for-size or up-sized with a new pipe in the same location. The techniques are most advantageous in cost terms when there are few lateral connections to be reconnected within a replacement section, when the old pipe is structurally deteriorated, when additional capacity is needed, and when restoration/environmental mitigation requirements are onerous.

In a typical pipe bursting operation, a cone-shaped tool ("bursting head") is inserted into the existing pipe and forced through it, fracturing the pipe and pushing its fragments into the surrounding soil. At the same time, a new pipe is either pulled or pushed in the annulus left by the expanding operation (depending on the type of the new pipe). In the vast majority of pipe bursting operations, the new pipe is pulled into place. The new pipe can be of the same size or larger than the replaced pipe. The rear of the bursting head is connected to the new pipe, and the front end of the bursting head to either a winching cable or a pulling rod assembly. The bursting head and the new pipe are launched from the insertion pit. The cable or rod assembly is pulled from the pulling or reception pit.

The leading or nose portion of the bursting head is often smaller in diameter than the existing pipe, to maintain alignment and to ensure a uniform burst. In order to facture the pipe, the base of the bursting head must be larger than the inside diameter of the existing pipe. It is also slightly larger than the outside diameter of the replacement pipe, to reduce friction on the new pipe and to provide space for maneuvering the pipe. The bursting head can be additionally equipped with expanding crushing arms, sectional ribs, or sharp blades, to further promote the bursting efficacy.

Sometimes an external protective sleeve pipe is installed during the bursting process, and the product pipe is installed within this casing or conduit pipe. This is normally only considered for pressure pipe installations. Alternately, in gravity sewer applications, the wall thickness of the product pipe is increased to allow for external scaring of the pipe as it is pulled into place. The bursting operation can proceed either continuously or in steps, depending on the applied type of pipe bursting system. Before bursting, the existing pipe should always be cleaned so that any sand or debris is removed (the required pull force will be reduced), and the service connections located and disconnected.

DECISION TO REPAIR, REHABILITATE OR REPLACE

Table 6 illustrates the advantages and limitations of above rehabilitation/replacement options. Tables 7 to 11 list the rehabilitation options for five different culvert materials based on the five condition states. It should be noted that culverts in Condition State 3 or higher and crossing a highway are recommended for replacement with a new culvert. However, a cost comparison with in-situ pipe replacement, such as pipe bursting, should be performed. Tables 7 to 11 also summarize the recommendations for rehabilitation and replacement of culverts that are identified with respect to the five condition states subjected to culvert size and length. The proposed rehabilitation technique would upgrade the Condition State, hence extending the service life. For instance, those culverts in Condition States 2 and 3 are upgraded to Condition States 1 and 2, respectively.

The proposed rehabilitation methods are based on culvert length and size. Culverts with small to medium size (i.e. 6-12 inches and 1-3 feet diameter) pose a challenge during inspection and rehabilitation, and may require the use of robots. The rehabilitation of small to medium sized culverts in Condition State 3 are identified based on culvert length (i.e. whether L<25ft. or L>25ft.). This differentiation is made considering the long-term effectiveness of the recommended technique.

Table 6 - Advantages and disadvantages of rehabilitation techniques

Technique		***Advantages***	***Disadvantages***
Cleaning and painting		Suits less abrasive conditions; paints enriched with zinc acts as a corrosion inhibitor, hence retards corrosion.	Requires intense cleaning and hence is costly and labor intensive. Weak spots act as sources of corrosion.
Invert paving	Asphalt paving	Suits less abrasive conditions.	Wears off with time; Contaminates runoff; Labor intensive.
	Concrete paving	Suits moderately abrasive bed loads.	May not act as a composite with metal pipe if invert corrosion takes place.
Pipe lining	Pre-cast concrete liners	The use of a smaller diameter section with improved hydraulic characteristics. May provide the required structural strength.	High handling costs; requires grouting to maintain contact.
	Plastic pipe liners	Easy to slide in. The use of a smaller diameter section with improved hydraulic characteristics.	Requires grouting between the liner and deteriorated pipe; No structural strength provided by the liner.
	Corrugated metal pipes	May be suitable for short sections and where temporary ponding is available.	Difficult to slide in; requires grouting between the liner and deteriorated pipe; though the diameter is reduced no gain in hydraulic characteristics.
	Fiberglass reinforced concrete liners	Easy to slide in. The use of a smaller diameter section with improved hydraulic characteristics.	Requires grouting between the liner and deteriorated pipe; No structural strength provided by the liner.
	Fiberglass reinforced plastic mortar pipes	Easy to slide in. The use of a smaller diameter section with improved hydraulic characteristics.	Requires grouting between the liner and deteriorated pipe; structural strength is provided by the pipe.
Liners cured in-situ	Cement mortar	No grouting is required. In-situ construction gives a smooth surface.	May not provide structural strength. Deterioration of metal pipe may result in cracking of liner and its removal.
	Cured in place liners	Quick and easy operation. Suitable for storm runoff and to carry chemical effluents.	Not suitable in abrasive environments. Does not provide structural strength.
In-situ pipe replacement	Pipe splitting	Quick and easy operation. Can be replaced with a pipe with similar diameter with improved hydraulic characteristics. Grouting is not required.	Requires special equipment. Surface heaving may take place during pipe replacement.
	Pipe eating	Quick and easy operation. Can be replaced with a pipe with similar diameter with improved hydraulic characteristics. Grouting is not required.	Requires special equipment.
	Pipe reaming	Best suited for thin corrugated metal pipes; quick and easy operation. Can be replaced with a pipe with similar diameter with improved hydraulic characteristics. Grouting is not required.	Requires special equipment.
Excavation and pipe replacement		A state-of-the-art new culvert designed and constructed to specification.	High cost of construction; interruptions; high cost due to road closure and subsequent road paving.

Table 7 - Recommended rehabilitation techniques based on condition state for concrete culverts

Condition State	Description	Implication	Culvert Size	Culvert Length	Recommended Technique	Improved Condition State
1	No visible deterioration	No structural defects.	All	All	No Action	
2	Circumferential crack, Moderate joint defects, i.e. open joint (medium) or joint displaced (medium), Surface damage – Slight spalling and wear.	Minimal collapse likelihood in short term but potential for further deterioration	All	All	Cleaning	
3	Fractured with no deformation or deformation <5%, Longitudinal or Multiple cracking, Minor loss of level, Severe joint defects, i.e. open joint (large) or joint displacement (large), Surface damage – Medium spalling and wear.	Collapse unlikely in near future but further deterioration likely	6 – 12 in.	All	Cleaning and spray grouting	2
			1 – 3 ft	L<=25 ft.	Cleaning, Invert paving and Pre-cast concrete lining or Cement mortar lining	2
				L>25 ft.	Cleaning and Sliplining with Fiberglass reinforced cement (FRC) lining or PVC lining	2
			> 3 ft.	All	Cleaning, Invert paving and Pre-cast concrete lining / Cement mortar lining / Fiberglass reinforced cement (FRC) lining / Cured-in-place flexible lining	2
4	Multiple fractures and deformation up to 10%, Serious loss of level and joint defects with voids or soils visible (open joint with >50mm soil or void visible or joint displacement >25% of diameter), Surface damage – Large spalling and wear.	Collapse likely in foreseeable future	6 – 12 in.	All	Cleaning and Sliplining with PVC pipe[+]	1[*]
			1 – 3 ft		Cleaning and rehabilitation with Fiberglass reinforced cement (FRP) pipe[+]	1[*]
			> 3 ft.			
5	Already collapsed or Fractured and deformed >10%.	Collapsed or collapse imminent	All	All	Replace with a new Culvert/pipe by excavation or trench less technology	1[*]

[*] **Condition State of new pipe material** [+] **To restore structural capacity**

Table 8 - Recommended rehabilitation techniques based on condition state for steel culverts

Condition State	Description	Implication	Culvert Size	Culvert Length	Recommended Technique	Improved Condition State
1	No visible deterioration	No structural defects.	All	All	No Action	
2	Minor surface deterioration less than or equal to 10 % (Surface rust or freckled rust)	Minimal collapse likelihood in short term but potential for further deterioration	All	All	Cleaning and painting	
3	Surface deterioration (Minor loss of section between 10% - 30%, severe Surface rust or freckled rust)	Collapse unlikely in near future but further deterioration likely	6 – 12 in.	All	Cleaning and painting	
			1 – 3 ft	L<=25 ft.	Cleaning, Invert paving and Cement mortar lining / Pre-cast concrete lining / Cured-in-place flexible lining	2
				L>25 ft.	Cleaning and Sliplining with PVC lining / Fiberglass reinforced cement (FRC) lining / Fiberglass plastic (FRP) lining	2
			> 3 ft.	All	Cleaning, Invert paving and Fiberglass reinforced plastic (FRP) lining / Cured-in-place flexible lining / Pre-cast concrete lining	2
4	Corroded with major surface deterioration (Major loss of section greater than 30%, Serious or advanced surface rust or freckled rust)	Collapse likely in foreseeable future	6 – 12 in.	All	Cleaning and Sliplining with PVC pipe⁺.	1*
			1 – 3 ft		Cleaning and rehabilitation with Fiberglass reinforced cement (FRC) pipe / Fiberglass plastic mortar (FRP) pipe⁺	1*
			> 3 ft.		Cleaning and rehabilitation with Fiberglass plastic mortar (FRP) pipe⁺	1*
5	Already locally collapsed or almost collapsing (Deformed, fractured and missing sections)	Collapsed or collapse imminent	All	All	Replace with a new Culvert/pipe by excavation or trench less technology	1*

*** Condition State of new pipe material ⁺ To restore structural capacity**

Table 9 - Recommended rehabilitation techniques based on condition state for aluminum culverts

Condition State	Description	Implication	Culvert Size	Culvert Length	Recommended Technique	Improved Condition State
1	No visible deterioration	No structural defects.	All	All	No Action	
2	Minor surface deterioration less than or equal to 10% (Surface oxidation or freckled oxidation)	Minimal collapse likelihood in short term but potential for further deterioration	All	All	Cleaning	
3	Surface deterioration (Minor loss of section between 10% - 30%, severe Surface oxidation or freckled oxidation)	Collapse unlikely in near future but further deterioration likely	6 – 12 in.	All	Cleaning	
			1 – 3 ft	L<=25 ft.	Cleaning, Invert paving and Pre-cast concrete lining / Cement mortar lining / Cured-in-place flexible lining	2
				L>25 ft.	Cleaning and PVC lining / Fiberglass reinforced cement (FRC) lining / Fiberglass reinforced plastic (FRP) lining	2
			> 3 ft.	All	Cleaning, Invert paving and Fiberglass reinforced cement (FRC) lining / Cured-in-place flexible lining / Pre-cast concrete lining	2
4	Corroded with major surface deterioration (Major loss of section greater than 30%, Serious or advanced surface oxidation or freckled oxidation)	Collapse likely in foreseeable future	6 – 12 in.	All	Cleaning and Sliplining with PVC pipe+.	1*
			1 – 3 ft > 3 ft.		Cleaning and rehabilitation with Fiberglass reinforced cement (FRC) pipe / Fiberglass reinforced plastic mortar (FRP) pipe +	1*
5	Already collapsed or almost collapsing (Deformed, fractured and missing sections)	Collapsed or collapse imminent	All	All	Replace with a new Culvert/pipe by excavation or trench less technology	1*

*** Condition State of new pipe material + To restore structural capacity**

Table 10 - Recommended rehabilitation techniques based on condition state for brick/clay culverts

Condition State	Description	Implication	Culvert Size	Culvert Length	Recommended Technique	Improved Condition State
1	No visible deterioration	No structural defects.	All	All	No Action	
2	Circumferential cracking, single longitudinal crack, Surface mortar loss (depth missing <15mm), Surface damage - Slight breaking away of small fragments from the surface (Spalling) and increased roughness (wear).	Minimal collapse likelihood in short term but potential for further deterioration	All	All	Cleaning	
3	Total mortar loss (depth missing >50mm), multiple longitudinal cracks at a single location, Single bricks displaced, Deformation <5%, Surface damage – Large areas of chipped brick (Medium spalling) or entire surface brick is missing (Medium wear).	Collapse unlikely in near future but further deterioration likely	1 – 3 ft	L<=25 ft.	Cleaning, Invert paving and Cement mortar lining	2
				L>25 ft.	Cleaning and Fiberglass reinforced cement (FRC) lining	2
			> 3 ft.	All	Cleaning, Invert paving and Cement mortar lining / Fiberglass reinforced cement (FRC) lining / Cured-in-place flexible lining	2
4	Total mortar loss (depth missing >50mm), Fractured with deformation up to 10%, Displaced/hanging brickwork, Small number of bricks missing, Dropped invert (drop > 20mm), Moderate loss of level, Surface damage – Entire brickwork is missing.	Collapse likely in foreseeable future	1 – 3 ft	All	Cleaning and rehabilitation with PVC pipe+	1*
			> 3 ft.		Cleaning and rehabilitation with Fiberglass reinforced cement (FRC) liner+	1*
5	Already collapsed, Missing invert, fractured with deformation >10%, extensive areas of missing brickwork.	Collapsed or collapse imminent	All	All	Replace using cured-in-place pipes or pipe bursting technology	1*

*** Condition State of new pipe material + To restore structural capacity**

Table 11 - Recommended rehabilitation techniques based on condition state for iron culverts

Condition State	Description	Implication	Culvert Size	Culvert Length	Recommended Technique	Improved Condition State
1	No visible deterioration	No structural defects.	All	All	No Action	
2	Minor surface deterioration less than or equal to 10 % (Surface rust or freckled rust with minimal cracks and graphitization)	Minimal collapse likelihood in short term but potential for further deterioration	All	All	Cleaning and painting	
3	Surface deterioration (Minor loss of section between 10% - 30%, severe Surface rust or freckled rust with multiple cracks and graphitization)	Collapse unlikely in near future but further deterioration likely	6 – 12 in.	All	Cleaning and painting	2
			1 – 3 ft	L<=25 ft.	Cleaning, Invert paving and Pre-cast concrete lining / Cement mortar lining / Cured-in-place flexible lining	2
				L>25 ft.	Cleaning, and PVC lining / Fiberglass reinforced cement (FRC) lining / Fiberglass reinforced plastic (FRP) lining	2
			> 3 ft.	All	Cleaning, Invert paving and Fiberglass reinforced cement (FRC) lining/ Cured-in-place flexible lining / Pre-cast concrete lining.	2
4	Corroded with major surface deterioration (Major loss of section greater than 30%, Serious or advanced surface rust or freckled rust with serious cracks graphitization)	Collapse likely in foreseeable future	6 – 12 in.	All	Cleaning and Sliplining with PVC pipe+	1*
			1 – 3 ft		Cleaning and rehabilitation with Fiberglass reinforced plastic mortar (FRP) pipe+	1*
			> 3 ft.		Cleaning and rehabilitation with Fiberglass reinforced plastic mortar (FRP) pipe+	1*
5	Already collapsed or almost collapsing (Deformed, fractured and missing sections graphitization)	Collapsed or collapse imminent	All	All	Replace with a new Culvert/pipe by excavation or trench less technology	1*

[*] Condition State of new pipe material [+] To restore structural capacity

CULVERT MANAGEMENT

Having established the Condition States of culverts in the network, the following financial information is required for culverts management decisions, where the following is known for the i^{th} culvert in the system.

- Number of culverts in the network (n where i=1,2,…, n)
- Age or date of installation with years inspected and cleaned (T_i)
- Year to be considered (t, where t=0 for the current year, and t=1 for the next year)
- Condition State of some of the culverts based on prior inspection
- Expected life (t_d or μ_i) and variance (σ_i) for each culvert based on Figure 3.
- Cost of installation for each culvert, it is also assumed to be the same as cost of replacement ($A_{i,t}$)
- Current value of the culvert after do nothing/rehabilitation/replacement ($B_{i,t}$)
- Cost of Circuitry ($C_{i,t}$)
- Cost of inspection for each culvert ($E_{i,t}$)
- Cost of rehabilitation for each culvert ($F_{i,t}$)
- User cost of failure for each culvert ($G_{i,t}$)
- User cost for each culvert ($H_{i,t}$)

The above also identifies information that is available from NJDOT, and the parameters that will be used in developing the CIMS. The CIMS developed uses a zero inflation rate and a zero discount rate for demonstration purposes. Specifically the cost of inspection, rehabilitation and inspection will be extracted from NJDOT bid documents.

Assessing the user cost or financial risk associated with failure is the most challenging issue in effective management of culverts. Though it can be argued that the cost or risk associated with failure is independent of culvert length, it may depend on culvert size, geographic location, whether it is laid along roadway or across roadway, and the proximity to critical structures such as subways, hospitals and hazardous waste sites. The user cost is usually associated with culvert failures, such as due to flooding, roadway collapses and ensuing traffic delays and expensive repairs. The flooding and associated detours and collateral damage are difficult to quantify. Besides, such damage claims can be paid by insurance, and hence not included in this pilot CIMS. Hence the CIMS developed includes only the roadway collapses and ensuing traffic delays and expensive repairs, which is applicable only for the culverts crossing highways. The NJDOT user cost manual describes the methodology to compute the use cost associated with the traffic delay due to extra travel time and extra travel distance. In addition to the above, once the culvert is failed it should be replaced with a new culvert. Hence the user cost developed in CIMS ($H_{i,t}$) will be the sum of the current cost of installation ($A_{i,t}$) plus the cost of detour during replacement if the culvert crosses main roads ($C_{i,t}$). Hence $H_{i,t}=A_{i,t}+C_{i,t}xU_{i,t}$ where $U_{i,t}$ is binary variable (0,1) such that $U_{i,t}=1$ if the culvert is crossing the road.

As per the NJDOT user cost manual, the Cost of Circuitry ($C_{i,t}$) has two components, i.e., circuitry delay and circuitry vehicle operating cost. Before computing the actual road user cost, the delay time through both the work zone and detour (if applicable) must be known. Although the number of vehicles delayed through the work zone and/or the detour has been determined, the amount of delay can only be computed after knowing the work zone and/or detour lengths and the times through them. The circuitry delay is only computed when a formal detour route has been established. The delay time through the work zone and through the detour are computed in the same manner. In each case, the delay is determined by subtracting the time it takes to travel either the work zone and/or detour when they are present, from the time it takes to travel the same distance when they are not present. The circuitry vehicle operating cost (VOC) is also only computed when a formal detour route has been established. At this point, an overall added travel length per vehicle has been determined. The circuitry VOC is computed by multiplying the number of vehicles that travel the detour, the overall added travel length per vehicle, and the current VOC cost rate associated with driving the added distance. The example given below shows how to compute the Cost of Circuitry ($C_{i,t}$). Please note that the values in bold are needed as input to compute $C_{i,t}$.

A **1.0** mile section of a two-lane coastal facility will be closed during a $15 million bridge replacement project. The facility carries **22,000** vehicles per day of which **80%** are passenger cars and 20% are trucks. A **9.0** mile detour will be in effect until construction is completed. It is estimated to take **100** days to complete construction. The existing facility is posted at **50** mph and the average speed through the detour route is **35** mph. The cost values are based on 1970 time value cost for car of $3 and that for truck $5 and VOC cost rate of $0.06 per mile for car and that of $0.12 for a truck. Those values needed to be updated to current values say for 2007 using escalation factors. Since it is difficult to find the current inflation for transportation component, we have taken the same escalation factor for time and distance. The escalation factors can be obtained from the Federal Reserve Bank of Minneapolis CPI calculator, which gives an escalation factor of 5.37. Hence the current time value cost for car of $16.11 and that for truck $26.85 and VOC cost rate of $0.32 per mile for car and that of $0.64 for a truck. Now one needs to compute the added time to travel the detour which is equal to 0.237 hours (=9/35-1/50) and the added travel length which is equal to 8 miles (=9-1). Hence the circuitry delay cost for all cars is $67,198 (=# cars x added time x time value=0.8x22,000x.237x16.11) and that for all trucks is $27,999 (=# trucks x added time x time value =0.2x22,000x.237x26.85). The circuitry VOC cost for all cars is $45,056 (=# of cars x added travel length x VOC cost=0.8x22,000x8x0.32) and that for all trucks is $22,528 (=# of trucks x added travel length x VOC cost=0.2x22,000x8x0.64). Hence the total is $162781. A 50% reduction is taken into account for uncertainties and multiplied by the number of days of construction to compute the Cost of Circuitry ($C_{i,t}$) of $8,139,050 (=total cost per day x reduction factor x # days=162,781x.5x100).

In estimating the user cost of failure one should take into account several aspects starting from the probability of failure of the given culvert, its location, and the consequences of such failures. Estimating $G_{i,t}$ is another challenge and requires a focused research effort. At this juncture, in order to develop the framework for analysis and without loss of generality it is assumed that $G_{i,t}$ is calculated based on user cost and the probability of failure, where $G_{i,t} = p_f x H_{i,t}$, where p_f is equal to the probability of failure obtained from equation 4 and equation 5 or Figure 3.

The objectives of the CIMS are to a) determine the optimum allocation of the current maintenance budget of $\$Z_t$, by identifying the culverts that are to be inspected, and those that are to be repaired, b) to estimate the minimum annual budget needed over a given planning horizon, and c) to comply with GASB-34 requirements. Also the CIMS should be capable of making project level decisions to repair, rehabilitate, replace, or do nothing for a given culvert. The following section lays the ground rules for project level decisions. For illustration purposes, the following are assumed for the current year for i^{th} culvert in the network. For a given culverts, the analysis shown below assumes that $\$H_{i,t}$ is known.

- Age of the culvert (T_i) = 10 years
- Current cost of installation ($A_{i,t}$) = $500,000
- Cost of inspection ($E_{i,t}$) = $30,000
- Cost of rehabilitation ($F_{i,t}$) = $200,000
- User cost ($H_{i,t}$) = $500,000

Project Level Decisions to Repair, Rehabilitate, Replace or Do Nothing

It is expected that the regional and field offices maintain records on culverts requiring inspection and rehabilitation/replacement. As stated before, yearly maintenance and rehabilitation work to be carried out in the current year is based on condition state of the culvert during the previous year. Figure 3 shows the variation of predicted survival probability of culverts with service time. The mathematical derivation for the above will be presented in a theoretical journal appropriate for such analysis while it is used in this report to illustrate the basis for management decisions. However, the authors emphasize on the need to generate such curves from historical field data and from accelerated laboratory tests (i.e. mimicking field conditions), during actual implementation. The decision to inspect, repair, rehabilitate, replace or do nothing depends on the current Condition State determined from culverts inspection. If the current Condition State is unknown due to budgetary constraints the selection is somewhat different, and is also listed below.

Inspect a Culvert of Unknown Condition State But Known Age

The proposed inspection frequency for culverts in New Jersey is given in Meegoda, et al., (2005). However, the above recommendations deviate from GASB-34 requirements. Hence justifications for such deviations should be made based on analysis. The proposed CIMS could perform such analysis but requires the age of the culverts. The proceeding section illustrates the rationale for decisions embedded in the proposed CIMS.

Suppose that the age of a corrugated steel culvert (t) is 9.3 years or t/td=0.31, where t_d=30 years. Hence the survival probability after 9.3 years is found to be 99%, and therefore, the failure probability is 1%. Hence the user cost of failure during the current budget period would be \$0.01x$H_{i,t}$ or \$$G_{i,t}$ (=\$500,000x0.01=\$5,000). If the decision is to inspect the culvert, then the current cost of inspection, \$$E_{i,t}$ (=\$3,000) has to be compared with cost of failure during the current budget period \$$G_{i,t}$. If the inspection cost (i.e., \$$E_{i,t}$) is less than \$$G_{i,t}$ then the decision to inspect is justified. In this example since \$3,000<\$5,000, the culvert has to be inspected. This example is illustrated in Table 12 (Culvert #2).

Rehabilitate/Replace a Culvert of Known Condition State But Unknown Age

Consider a corrugated steel culvert of unknown service life in Condition State 2 or survival probability of 70%. This would give a t/t_d value of 0.825, and hence a remaining service life of $t_d(1- t/t_d)$ 30*0.675 = 20.25 years. Hence the current worth of a given culvert is \$$B_{i,t}$, which is computed based on survival probability, and is computed as \$$B_{i,t}$ = \$$A_{i,t}$x0.7 (= 500,000x0.7 = \$350,500). If the culvert is to be repaired, the cost of rehabilitation, \$$F_{i,t}$ =\$200,000 and \$$B_{i,t}$ have to be compared with current value of the rehabilitated culvert. Rehabilitation upgrades the Condition State by one state, giving a t/td value of 0.6 and a survival probability of 90%, and hence a new remaining service life of 0.9x30 = 27 years. This gives the worth of the culvert after repair to be \$$C_{i,t}$ = \$$A_{i,t}$x0.9 (=500,000x0.9 = \$450,000). If after rehabilitation (i.e., \$$C_{i,t}$) it is worth more than \$$B_{i,t}$+\$$F_{i,t}$, then the decision to rehabilitate is justified. In this example, the proposed rehabilitation cannot be justified since (\$200,000+\$350,000)>\$450,000. This example is illustrated in Table 12 (Culvert #7).

Rehabilitate/Replace a Culvert of Unknown Condition State and Known Age

When the condition state is not known, it is required to know the age of pipe, and the analysis is different than that described above. For a 15 year old corrugated steel culvert the survival probability is 95.639%, and hence the failure probability is 4.361%. Therefore, the user cost of failure for the current budget period would be \$0.04361x$H_{i,t}$ or \$$G_{i,t}$ (=\$500,000x0.04361=\$21,805). If the decision is to repair the culvert, then current cost of rehabilitation, \$$F_{i,t}$ (=\$200,000) has to be compared with cost of failure \$$G_{i,t}$. If the rehabilitation cost (i.e., \$$F_{i,t}$) is less than \$$G_{i,t}$ then the decision to repair is justified. In this example since \$200,000>\$21,805 there is no justification for the proposed rehabilitation. However, it is strongly recommended to perform an inspection to determine the condition state. This example is illustrated in Table 12 (Culvert #6).

Rehabilitate/Replace a Culvert of Known Condition State and Known Age

When the condition state and the service age of the culvert is known, the analysis is also different than that described above. For a 15 year old corrugated steel culvert in Condition State 2, the t/td value is 0.825 and hence remaining service life is 30x0.675 =20.25 years with the factor of safety. Please note that although based on the service life of 15 years, it should have a remaining life of 30 years, the prediction based on condition state dominates. Hence the actual remaining life is considered to be 20.25 years. The current worth of a given culvert is $\$B_{i,t}$, which is computed based on survival probability, hence it is $\$B_{i,t} = \$A_{i,t}x0.70$ (= $750,000*0.70 = $525,000). If the culverts is to be repaired the cost of rehabilitation, $\$F_{i,t}$ (=$200,000) and $\$B_{i,t}$ have to be compared with current value of rehabilitated culverts. Rehabilitation upgrades the Condition State by one state, giving a t/td value of 0.6, and hence a new remaining service life of 0.9x30 = 27 years. This gives the worth of the culvert after repair to be $\$C_{i,t} = \$A_{i,t}x\ 0.90$ (=$750,000x0.9 = $675,000). If after rehabilitation (i.e., $\$C_{i,t}$) it is worth more than $\$B_{i,t}+\$F_{i,t}$, then the decision to rehabilitate is justified. In this example since ($200,000+$525,000)>$675,000, proposed rehabilitation cannot be justified. This example is illustrated in Table 12 (Culvert #5).

Network Level Decisions to Repair, Rehabilitate, Replace or Do Nothing

The state DOTs are generally responsible in assessing recommendations made by regional and field offices on culvert inspection and rehabilitation/replacement, and these are to be examined and prioritized while adhering to budgetary allocations. These decisions should best utilize the funds allocated for the planning horizon, thus resulting in a net improvement in total network asset value. This aspect will be addressed during future research.

The following section presents a preliminary model that meets the aforementioned objectives. For a given budget $\$Z_t$, the model optimizes the network performance based on the stipulated maintenance policies. These policies are associated with incurred costs. The decisions to be made depend on the state of deterioration of culvert pipe and can be identified as cost of inspection $E_{i,t}$, cost of rehabilitation/replacement $F_{i,t}$, current value of the culvert after do nothing/rehabilitation/replacement $B_{i,t}$, and cost of no-action leaving it to deteriorate $G_{i,t}$, where t is the year in consideration. Hence the objective is expressed mathematically as:

$$\text{Maximize } \Sigma [B_{i,t} - G_{i,t} X_{i,t} Y_{i,t}] \qquad (6)$$

$$\text{Subjected to } Z_t, \geq \Sigma [F_{i,t} X_{i,t} (1- Y_{i,t}) + E_{i,t} (1- X_{i,t})] \qquad (7)$$

where $X_{i,t}$, $Y_{i,t}$ are binary variables (0,1) such that $X_{i,t}$=0 if there is inspection and $Y_{i,t}$=0 if there is rehabilitation/replacement.

Table 13 provides network level actions for ten culverts with $1,000,000 budget, and the proposed actions will cost $662,000. This value is much lower than the allocate budget hence culverts 6, 8, and 10, should be inspected and most critical one should be repaired. The above optimization should be conducted on June 30th of each year. At this time one needs to visit Federal Reserve Bank of Minneapolis web site for CPI calculator to compute the escalation factor that year to be used in user cost calculations.

Please note that the result of the above network analysis may not maintain the overall condition state of the system. In that regard, a long-term strategy should be implemented such that net improvements to the total network asset value is either maintained or increased.

Table 12 - Culvert cost information and project level inspection/rehabilitation/replacement costs

Culvert #	*Culvert Type*	*Years in Service (T_i)*	*Condition State*	*Estimated Remaining Service Life*	*Current cost of installation ($\$A_{i,t}$)*	*Cost of inspection ($\$E_{i,t}$)*	*Cost of rehabilitation ($\$F_{i,t}$)*	*User cost of failure ($\$G_{i,t}$)*	*Project Level Decision*
1	CSCP	5	Not Known	40	500,000	3,000	200,000	-	Do Nothing
2	CSCP	9.3	Not Known	30.7	500,000	3,000	200,000	5,000	Inspect
3	CSCP	15	I	33	750,000	5,000	200,000	75,000	Do Nothing
4	CSCP	Not Known	III	15	1,200,000	10,000	200,000	600,000	Repair
5	CSCP	15	II	20.25	750,000	5,000	200,000	225,000	Do Nothing
6	CSCP	15	Not Known	30	750,000	5,000	200,000	42,000	Inspect to obtain condition state for a decision
7	CSCP	Not Known	II	20.25	500,000	3,000	200,000	150,000	Do Nothing
8	CSCP	24	Not Known	21	650,000	4,000	200,000	173,500	Inspect to obtain condition state for a decision
9	CSCP	Not Known	IV	10.5	450,000	3,000	175,000	315,000	Replace
10	CSCP	28	Not Known	17	450,000	3,000	175,000	189,000	Inspect to obtain condition state for a decision

Table 13 - Project and network level costs

Culvert #	*Project Level Cost*	*Network Level Cost*	*Network Level Decision*
1	0.00	0.00	Do Nothing
2	3,000	3,000	Inspect
3	0.00	0.00	Do Nothing
4	200,000	200,000	Repair
5	0.00	0.00	Do Nothing
6	5,000 or 205,000	5,000	Inspect
7	0.00	0.00	Do Nothing
8	3,000 or 203,000	3,000	Inspect
9	450,000	450,000	Replace
10	3,000 or 203,000	3,000	Inspect
Total	$664,000 to $1264,000	$664.000	

As mentioned before, the framework proposed here represents a preliminary approach to asset management of a network of culverts. Future research is expected to focus on field studies to obtain the necessary cost parameters for deteriorating culvert pipes and to perform a statistical analysis of the sample. These investigations are necessary for model refinements that will be developed during the next phase of this research and will utilize a variety of operations research tools as well as simulation experiments as deemed necessary.

ENHANCEMENTS TO THE CULVERT INFORMATION MANAGEMENT SYSTEM (CIMS)

Utilizing all the concepts described above a Culvert Information Management System (CIMS) was developed at NJIT and the following sections describe the features and functionality of that system. This system was an enhancement of the system NJIT developed for the previous NJDOT project entitled "Corrugated Steel Culvert Pipe Deterioration." Hence only the enhancement is described in the following sections. Therefore, first time reader is directed to the final report of our previous project for the full description of the CIMS.

Culvert Assessment Module

A culvert assessment module was developed to perform financial analysis. If one clicks 'Assessment Form' button on culvert single record form in CIMS (see Figure 4) to open the Culvert/Network Assessment Form (see Figure 5). This form summarizes the pipe's material type, current condition, treatment cost, and relevant date information for user to make operational decisions such as if the culvert needs inspection or rehabilitation treatment.

From the current pipe condition (indicated by Inspection_condition field) and pipe age (calculated by the Installation_date) from Figure 4, the CIMS will automatically take into account all available data about the selected culvert segment and reference to the culvert treatment policies defined in tables 7-11.

If needed, users can click the 'Modify Costs' button (Figure 5) to open the Modify Cost Parameters form (Figure 5.1) to make adjustments. On this form, clicking the last 'Help' button will lead the user to a sub-module, 'User_failure_Cost'. This module will guide users step-by-step to estimate the Do_nothing cost used for the assessment process. Clicking other 'Help' buttons will open corresponding cost calculation modules to assist users to figure out each cost category value that is needed for pipe/culvert assessment. The details of these modules as well as the business logic behind the assessment processes are summarized in Appendix 3 of the CIMS user training manual.

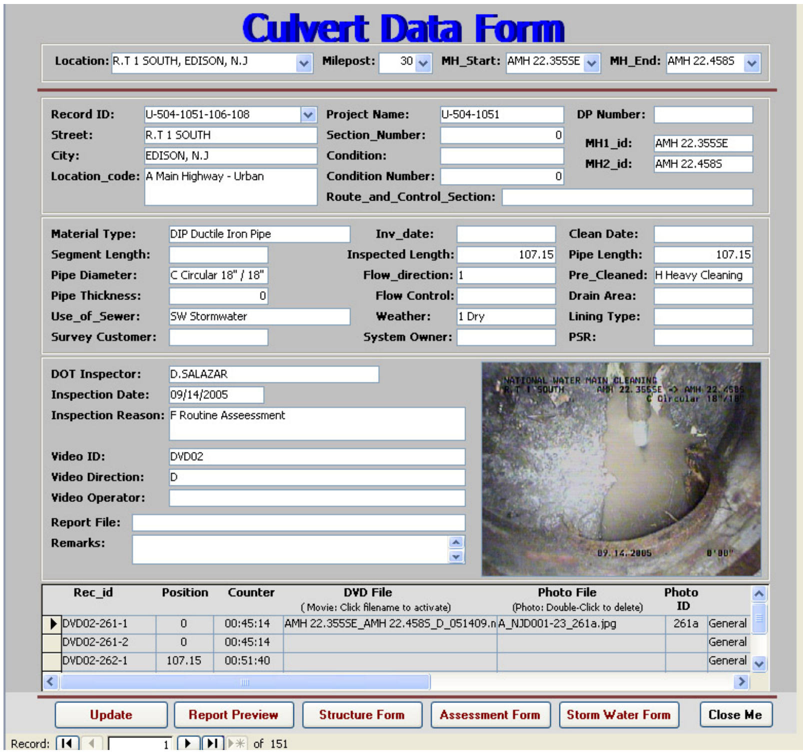


Figure 4. Culvert segment data form

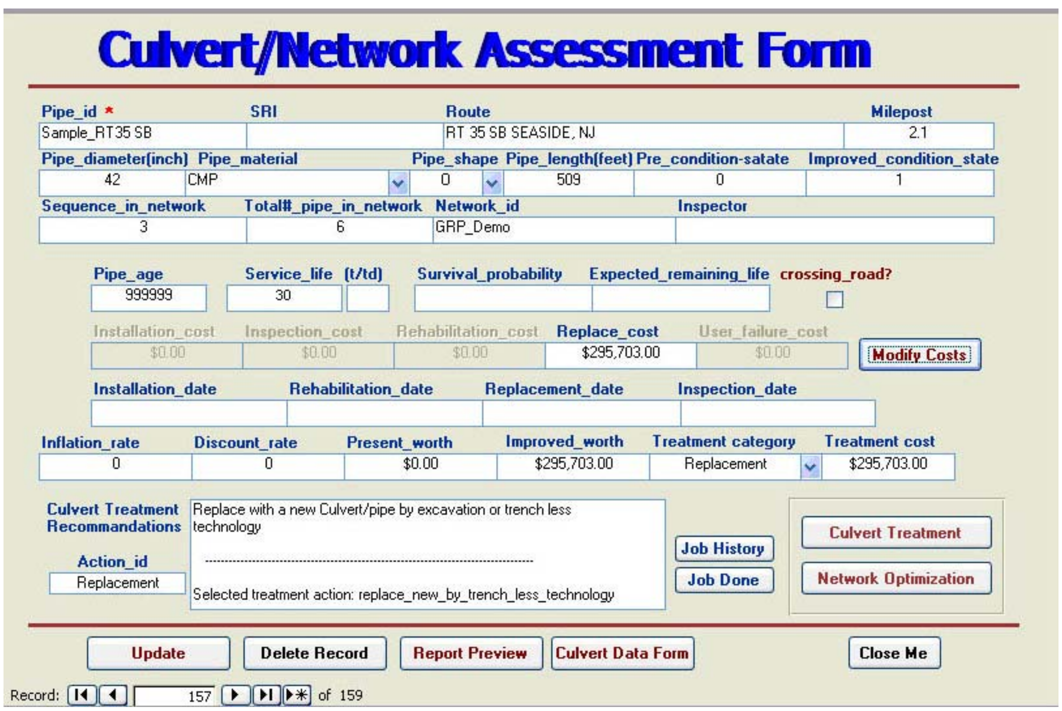


Figure 5. Culvert/Network assessment form

Combined with Risk_Factor based on Condition State and User_Failure_Cost, the system lists all suitable treatment techniques for users to select and compares their corresponding expenses. Based on the comparison, CIMS will recommend or deny the user selection and remind the user to check existing data sets.

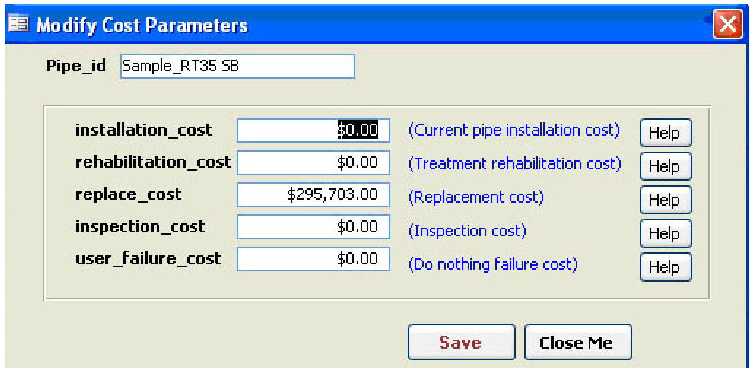


Figure 5.1. Modify costs parameters form

By clicking the ‘Culvert Data Form’ button on the Culvert/Network Assessment Form (Figure 5) will cause several different responses depending on the pipe condition state as well as its age. Either user will receive simple messages such as “Inspection!”, “Replacement!” for cases where the pipe treatments are easily determined or the process will open additional forms for further investigation.

In cases where both the current condition and age of the pipe are known, the Recommended Treatment form will open (Figure 5.2). On this form, the recommended techniques, and the current and improved conditions as retrieved from the treatment policy table are displayed. Users can select desired techniques and click ‘Confirm Treatment Technique’ button for cost justification (Figure 5.3).

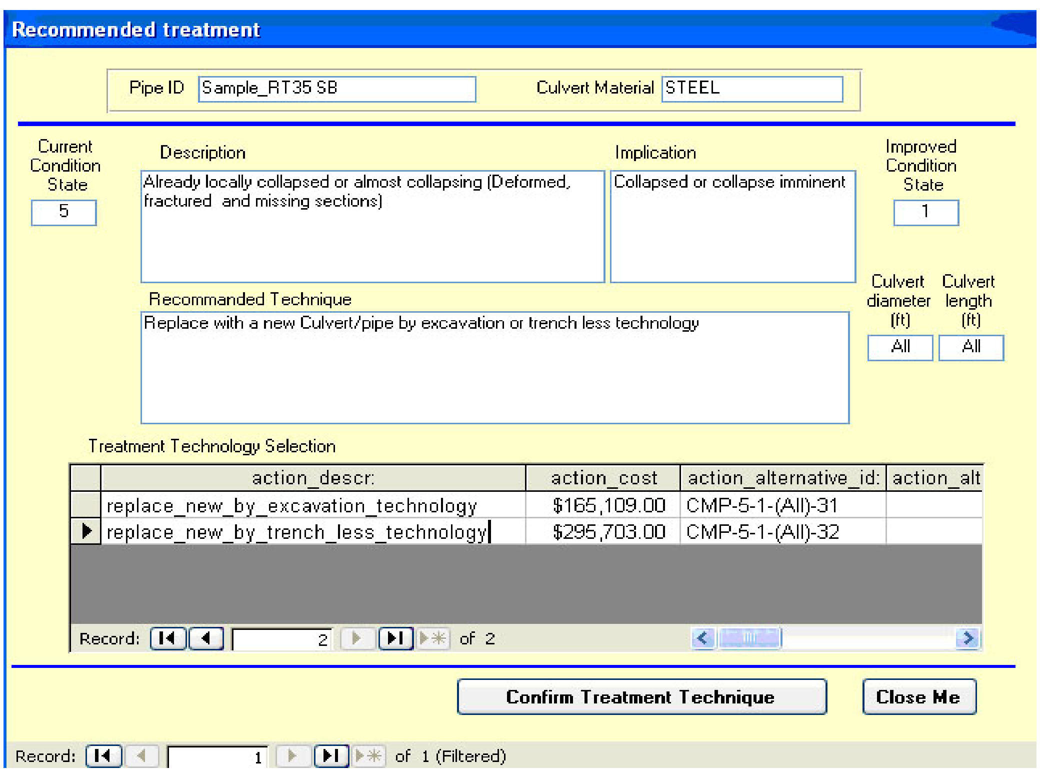


Figure 5.2. Recommended treatment form

CIMS will automatically compare selected treatment technique costs (Action Costs) to Do_Nothing_Cost (i.e., User_Failure_Cost) and make a judgment if the selected action is justified (indicated by text fields under title ‘Justified’). Users can make a choice to either accept the recommendation, or not, by double clicking the corresponding text box under title ‘Select’. Only one action can be selected as 'Y' (Yes). If the selection is justified, the recommend treatment technique will be saved in the decision comment text box and transferred back to the database. The decisions will show up on the Culvert/Network Assessment Form (Figure 5) for the user to review.

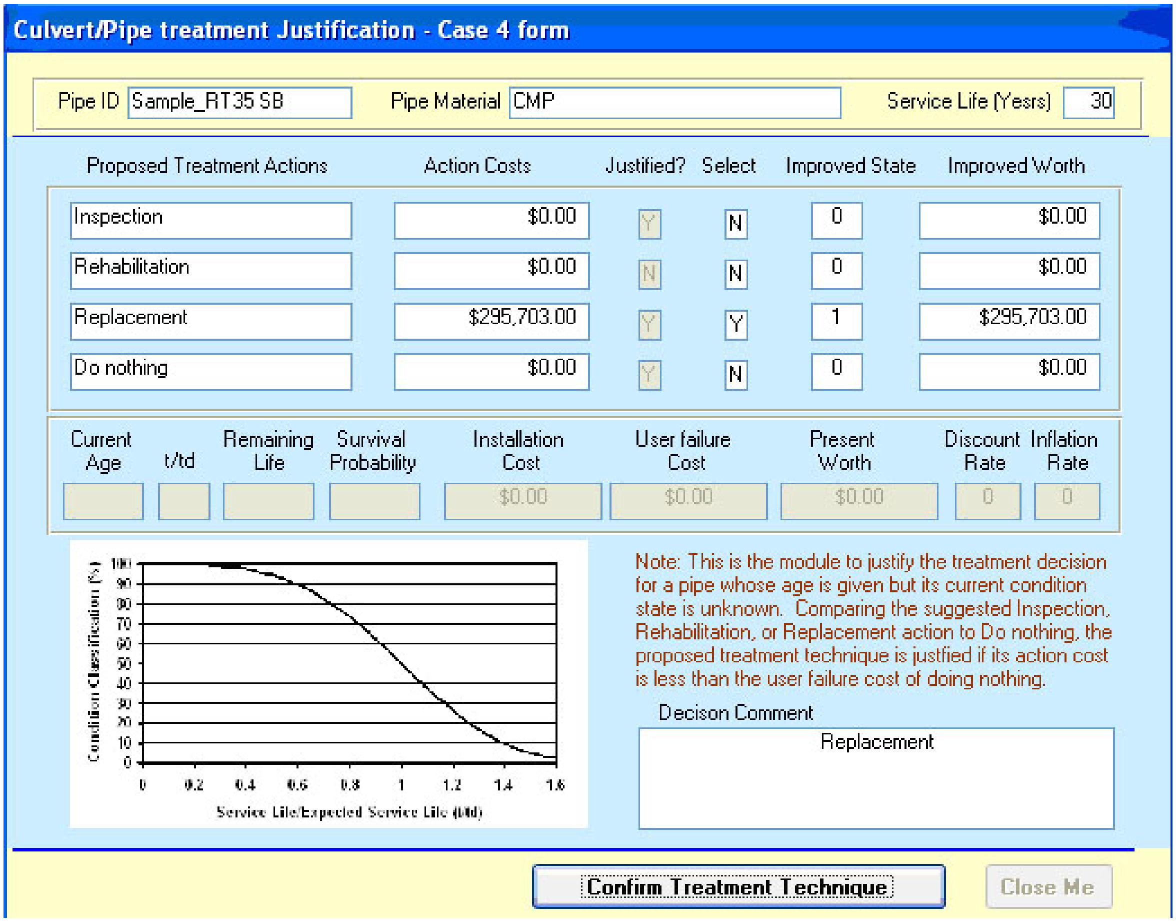


Figure 5.3. Culvert/Pipe treatment cost justification form

Optimization Module

After determining the treatment techniques for the culvert/pipe segments under consideration, the user can define project groups and search the optimal or near optimal solutions for budget allocation. This will be done by the CIMS optimization module.

Clicking the 'Network Optimization' button on the Culvert/Network Assessment Form (Figure 5) will open a switchboard form 'Optimization Module Switchboard Form' to start the budget optimal allocation process (Figure 6).

Clicking 'Define Network' on the form will group the culvert segments and open the Culvert Network Selection form (Figure 6.1). On this form, all culvert segments that have been assigned treatment techniques will be listed, including 'Not Determined' and 'Do nothing'.

By excluding the 'Not Determined' and 'Do nothing' segments, users can arbitrarily select (by clicking the box under title 'Selected') a group of culverts as the elements of a network (or called a project). Also, the user can decide if some of the selected segments must be included in the optimal solution no matter how much they cost (by clicking the box under the title 'Pre-fixed'). Figure 6.1 illustrates a sample case.

After all selections have been made, clicking the 'Confirm Selection' button will filter the list by 'Selected' only. In addition, the filtered list may be re-ordered by listing the 'Pre-fixed' first, then ordering all segments by their Treatment Costs in descending order.

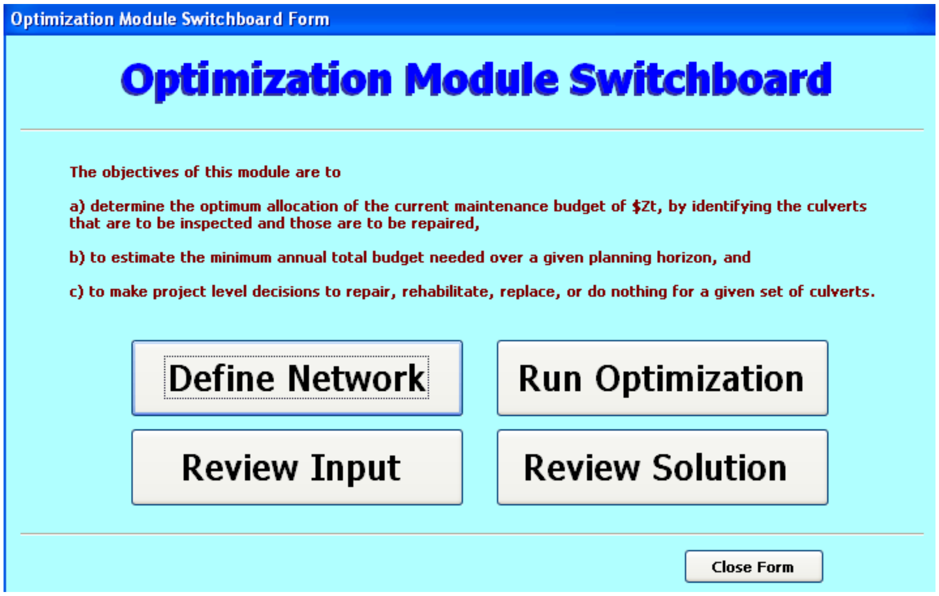
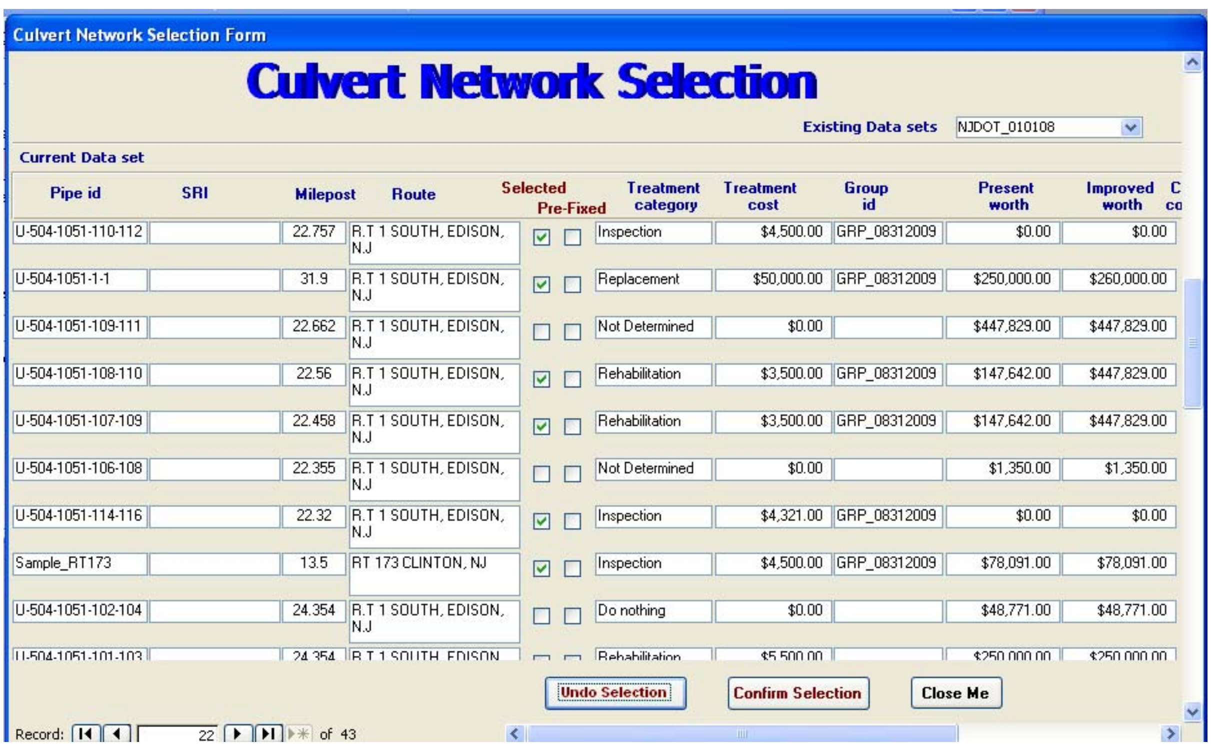


Figure 6. Optimization module switchboard form



Pipe id	SRI	Milepost	Route	Selected	Pre-Fixed	Treatment category	Treatment cost	Group id	Present worth	Improved worth
U-504-1051-110-112		22.757	R.T 1 SOUTH, EDISON, NJ	☑	☐	Inspection	$4,500.00	GRP_08312009	$0.00	$0.00
U-504-1051-1-1		31.9	R.T 1 SOUTH, EDISON, NJ	☑	☐	Replacement	$50,000.00	GRP_08312009	$250,000.00	$260,000.00
U-504-1051-109-111		22.662	R.T 1 SOUTH, EDISON, NJ	☐	☐	Not Determined	$0.00		$447,829.00	$447,829.00
U-504-1051-108-110		22.56	R.T 1 SOUTH, EDISON, NJ	☑	☐	Rehabilitation	$3,500.00	GRP_08312009	$147,642.00	$447,829.00
U-504-1051-107-109		22.458	R.T 1 SOUTH, EDISON, NJ	☑	☐	Rehabilitation	$3,500.00	GRP_08312009	$147,642.00	$447,829.00
U-504-1051-106-108		22.355	R.T 1 SOUTH, EDISON, NJ	☐	☐	Not Determined	$0.00		$1,350.00	$1,350.00
U-504-1051-114-116		22.32	R.T 1 SOUTH, EDISON, NJ	☑	☐	Inspection	$4,321.00	GRP_08312009	$0.00	$0.00
Sample_RT173		13.5	RT 173 CLINTON, NJ	☑	☐	Inspection	$4,500.00	GRP_08312009	$78,091.00	$78,091.00
U-504-1051-102-104		24.354	R.T 1 SOUTH, EDISON, NJ	☐	☐	Do nothing	$0.00		$48,771.00	$48,771.00
U-504-1051-101-103		24.354	R.T 1 SOUTH, EDISON			Rehabilitation	$5,500.00		$250,000.00	$250,000.00

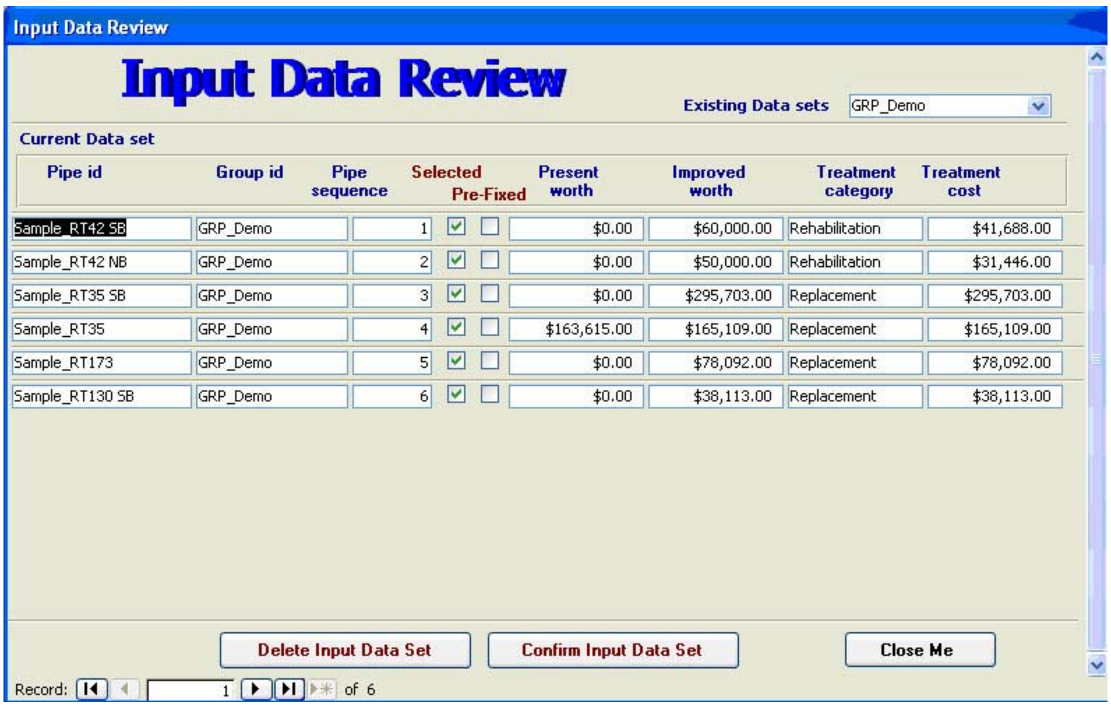
Figure 6.1. Culvert network selection form

After a network has been defined, clicking the 'Review Input' button on the 'Optimization Module Switchboard Form' (Figure 6) will allow the user to review the network input data set (see Input Data Review form, Figure 6.2). Users can do last minute changes on the form and send the confirmed input data set to optimization solution module tables.

Then, clicking the 'Run Optimization' button on the 'Optimization Module Switchboard Form' (Figure 6) will open the optimization module main form, 'Culvert Project Optimization' (Figure 6.3).

The 'Culvert Project Optimization' form has four major components:

On the top – the system evaluates the input data set and summarizes its major attributions, e.g., how many culvert segments are in the network, what is the total capital required by these segments, and how many pre-fixed segments as well as the minimum required budget for these prefixed culverts. In the upper segment of the form (Project_Input_Dataset) the input data set is displayed. In the lower segment of the form (ILP_Model_Solution) the solution results will display after running algorithms. At the bottom, a short label will state the final solution summary values.


Input Data Review

Input Data Review

Existing Data sets: GRP_Demo

Current Data set

Pipe id	Group id	Pipe sequence	Selected	Pre-Fixed	Present worth	Improved worth	Treatment category	Treatment cost
Sample_RT42 SB	GRP_Demo	1	☑	☐	$0.00	$60,000.00	Rehabilitation	$41,688.00
Sample_RT42 NB	GRP_Demo	2	☑	☐	$0.00	$50,000.00	Rehabilitation	$31,446.00
Sample_RT35 SB	GRP_Demo	3	☑	☐	$0.00	$295,703.00	Replacement	$295,703.00
Sample_RT35	GRP_Demo	4	☑	☐	$163,615.00	$165,109.00	Replacement	$165,109.00
Sample_RT173	GRP_Demo	5	☑	☐	$0.00	$78,092.00	Replacement	$78,092.00
Sample_RT130 SB	GRP_Demo	6	☑	☐	$0.00	$38,113.00	Replacement	$38,113.00

Delete Input Data Set | Confirm Input Data Set | Close Me

Record: 1 of 6

Figure 6.2. Input data review form

Under the form title, users can use the combo box 'Project Group ID' to retrieve previously created network data sets and display their results in the sub-forms. Note that the user should enter available total budgets for specified network (Project) data set in the textbox 'Total Budget Available ($)'.

Between the two sub_forms, there are two command buttons: 'Search Optimal Solution' and 'Project Solution Report'. Click the 'Search Optimal Solution' button to run either a '0-1 Implicit Enumeration' procedure to find real optimal solution or a heuristic procedure, named as 'Catch-Big-Fish', to obtain a near-optimal solution. Both procedures were programmed by NJIT Research Team.

The '0-1 Implicit Enumeration' program is based on the foundation of Egon Balas (Balas 1965). It enumerates all possible combinations of the decision variables and compares their resulting objective function values to determine the real optimal solution.

On the other hand, the heuristic procedure, 'Catch-Big-Fish', simply sorts the selected culvert projects by their capital requirements in descending order. Then, it add up the bigger capital requirements one by one from the top of the list to the bottom until the summation of the total capital required for these projects is just over the available budget. At this moment, all the summarized projects except the last one will be labeled as the members of the network selection candidates. Thus, the heuristics will catch-up the most costly projects (so called 'Big-Fish') without exceeding the budget limit.

The reason to have two algorithms is that the real-optimal solution for the integer program problem has 2^N computational complexity. Although the objective function and budget constraint are both simple linear additions, it may take a long time to evaluate all possible combinations when N gets too big. Therefore, we recommend using the heuristic when N>25. The heuristic covers the more costly segments first then the smaller ones until the available budget runs out.

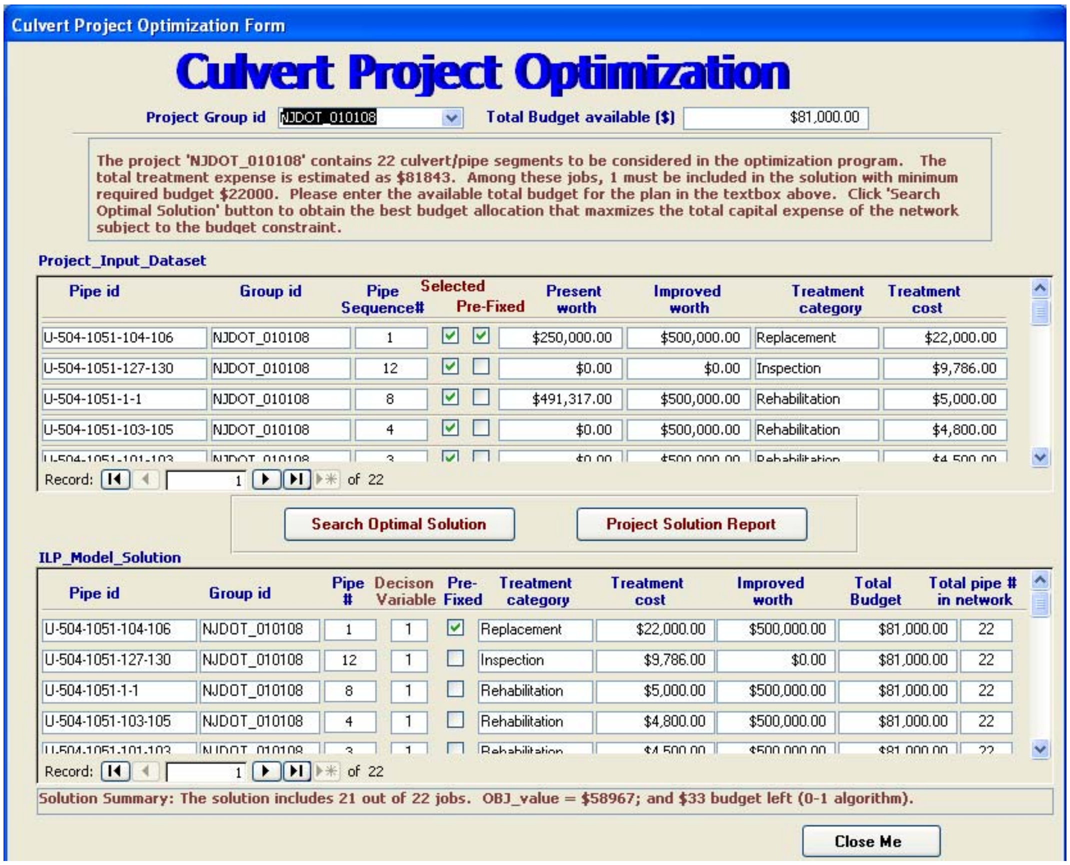


Figure 6.3. Culvert project optimization form

Figure 6.4 displays a sample Solution Report. The report layout and its contents may be modified to meet customer requirements.

SUGGESTIONS FOR FUTURE RESEARCH

This project is a limited scope demonstration project of implementing the culvert information management system. There are several aspects that need further research and implementation. They are listed below.

1. The proposed culvert information management system was developed in association with the NJDOT straight line database. This should be upgraded to a database based on a geographic information system.

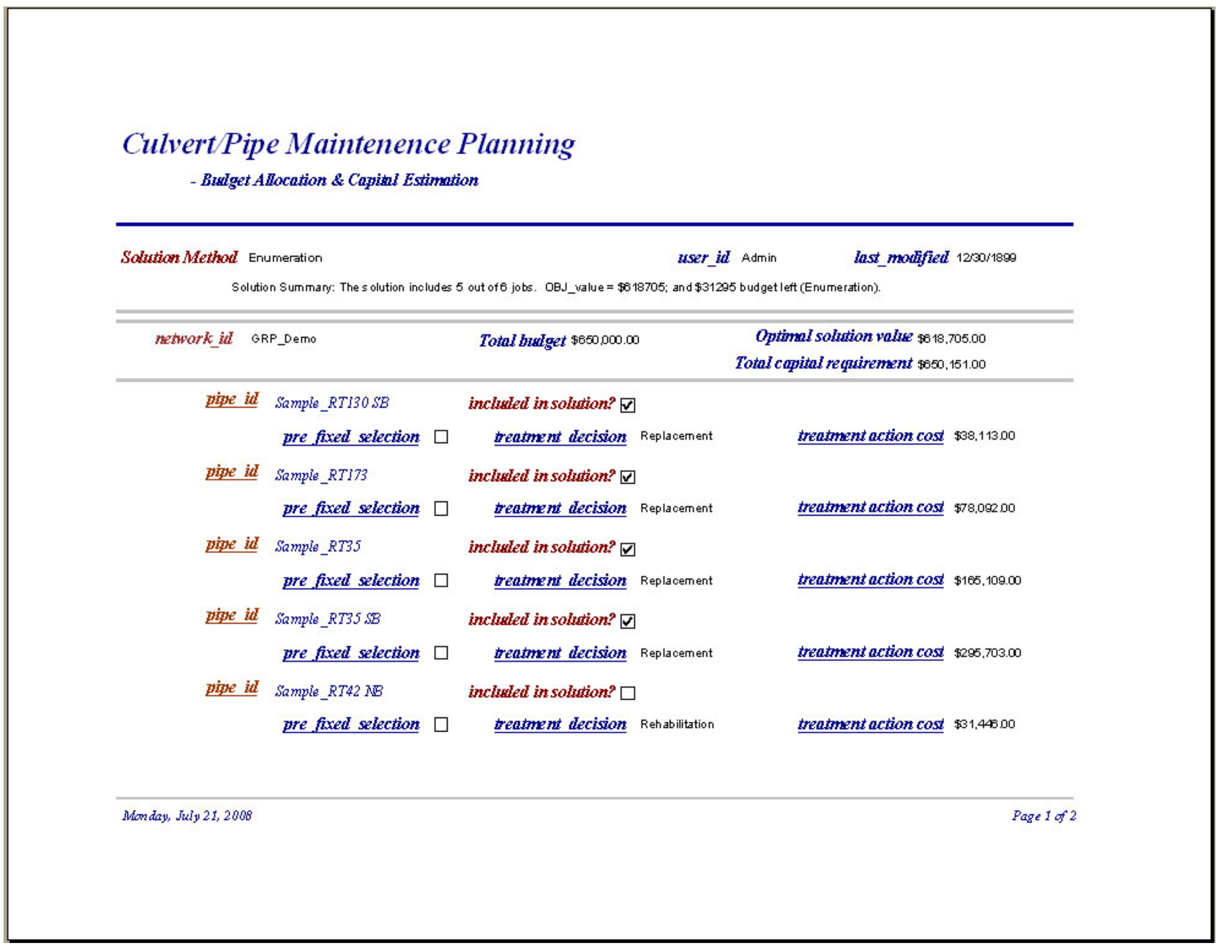
2. The culvert information management system developed in this demonstration project contains only the culverts inspected to date. To perform system wide optimization, one needs all information on all culverts in the state of New Jersey. Until that information is available, the

proposed system is unable to perform system wide optimization to comply with GASB 34 requirements. Hence, any future research should include the development of this component.

3. The proposed CIMS only considers in-kind replacement, which is not always possible. Therefore, the system should be upgraded to include replacement with different types of culverts.

4. Most of the culverts are not inspected during the current year. Hence, a mechanism should be developed to predict the current condition state based on the past condition state. This involves substantial mathematical analysis, and hence it is proposed to be included in future developments.

5. Based on the current NJDOT administrative structure, capital investments and maintenance expenditure occur in two separate departments. However, the program assumes funds for both come from one source, hence the department should consider changing the administrative structure or in the future, programs should split this into two separate optimizations.



Culvert/Pipe Maintenence Planning
- Budget Allocation & Capital Estimation

Solution Method Enumeration | user_id Admin | last_modified 12/30/1899

Solution Summary: The solution includes 5 out of 6 jobs. OBJ_value = $618705; and $31295 budget left (Enumeration).

network_id GRP_Demo | Total budget $650,000.00 | Optimal solution value $618,705.00
Total capital requirement $650,151.00

pipe_id Sample_RT130 SB | included in solution? ☑
pre_fixed_selection ☐ | treatment_decision Replacement | treatment action cost $38,113.00

pipe_id Sample_RT173 | included in solution? ☑
pre_fixed_selection ☐ | treatment_decision Replacement | treatment action cost $78,092.00

pipe_id Sample_RT35 | included in solution? ☑
pre_fixed_selection ☐ | treatment_decision Replacement | treatment action cost $165,109.00

pipe_id Sample_RT35 SB | included in solution? ☑
pre_fixed_selection ☐ | treatment_decision Replacement | treatment action cost $295,703.00

pipe_id Sample_RT42 NB | included in solution? ☐
pre_fixed_selection ☐ | treatment_decision Rehabilitation | treatment action cost $31,446.00

Monday, July 21, 2008 | Page 1 of 2

Figure 6.4. Sample solution report

SUMMARY AND CONCLUSIONS

The following are the conclusions of this research:

1. Information on management systems for underground infrastructure such as pipes and culverts is limited. Earlier works have found that both structural and serviceability conditions need to be considered when formulating a management strategy for a storm water network.

2. In this research, culvert deterioration is defined based on the Condition States, and the assumption that life added through rehabilitation results in an upgrade of the Condition State.

3. Proposed rehabilitation methods are based on culvert length and diameter. Culverts with small to medium size diameters (i.e. 6-12 inches and 1-3 feet diameter) may require the use of robots for inspection and rehabilitation. In addition, small to medium sized culverts in Condition State 3 are differentiated based on pipe length (i.e. whether L<25ft or L>25ft).

4. The reliability of the culvert is the probability that it will operate for a specific period of time, e.g., its design life, under its design conditions without a failure. The Weibull distribution was chosen to model the reliability of the culvert. We applied this approach to estimate the remaining service life of several types of culverts by using the design life of the material type to normalize the cumulative distribution function of failure. The variation of condition state with normalized life (t/ td) is plotted for the five types of culvert materials in Figure 3. This plot shows that the proposed theory could represent the culvert performance data for five different culvert material types used.

5. The CIMS optimizes the allocation of annual maintenance budgets by determining the culverts needing inspection and rehabilitation/replacement. In addition, the CIMS can be used to make project level decisions to inspect, rehabilitate/replace, or do nothing.

6. Recommendations for culvert inspection or rehabilitation/replacement need to be assessed and prioritized while adhering to budgetary allocations, and minimizing risks and costs associated with failure.

7. A limited scope pilot scale CIMS was developed, tested and implemented for NJDOT

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