CORRUGATED STEEL CULVERT PIPE DETERIORATION

FINAL REPORT
August 2009

Submitted by

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In cooperation with

New Jersey
Department of Transportation
Bureau of Research
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U.S. Department of Transportation
Federal Highway Administration

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1. Report No. FHWA-NJ-2006-007	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Corrugated Steel Culvert Pipe Deterioration		5. Report Date August 2009
		6. Performing Organization Code
7. Author(s) Jay N. Meegoda, Thomas M. Juliano		8. Performing Organization Report No.
9. Performing Organization Name and Address National Center for Transportation and Industrial Productivity New Jersey Institute of Technology University Heights, Newark, NJ 07102-1982		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address New Jersey Department of Transportation Federal Highway Administration P.O. Box 600 U.S. Department of Transportation Trenton, NJ 08625 Washington, D.C.		13. Type of Report and Period Covered Final Report January 2003 to December 2006
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This research provides the basis for developing a comprehensive plan for inspection, cleaning, condition assessment and prediction of remaining service life of CSCP (Corrugated Steel Culvert Pipe). Inspection frequency guidelines were developed that rate CSCP's at three levels. The rating categories are based on the following factors: corrosion and erosion, bed load, pH, and culvert size, age and importance, and are ranked according to increasing need; e.g., annual inspections are recommended for Category III (older pipes with reported problems). A four condition state assessment system based upon the Caltrans system was developed, including quantifiable section losses, specific surface features, and a prescribed response associated with each condition state. A Markov deterioration model was used to predict the future condition state of new CSCP in urban and rural settings. These improvements will be addressed in the next phase of the research project within the context of a Culvert Information Management System (CIMS). In addition, the Weibull distribution will replace the Markov model for predicting the remaining service life of CSCP in the next phase of this project.

The proposed CIMS will be capable of analyzing decisions to inspect, rehabilitate/replace, or do nothing at both project and network levels. At the project level this will be achieved by comparing inspection and/or rehabilitation/replacement costs with risks and costs associated with failure. At the network level, the associated costs will be optimized to meet annual maintenance budget allocations by prioritizing CSCP's needing inspection and rehabilitation/replacement. CIMS will also be used to estimate the required annual budgetary allocation for a stipulated planning horizon to maintain or improve the aggregate condition state of the CSCP network, or to maintain or improve the total highway CSCP network asset value, thereby meeting the GASB-34 requirements. The optimum sequential path in the annual decision making process may then be determined using a combination of operations research tools.

A framework for real time and automated monitoring of the condition of culverts based on the identification of internal defects via video inspection was developed. An innovative approach of judiciously extracting image frames from the video and analyzing the frames to locate and categorize major defects was developed. Each frame is preprocessed to enhance contrast using an adaptive scheme and reduced dimensionality in pixel-space by implementing region based processing. The preprocessing is followed by a two-step image segmentation process, which implements a background elimination procedure in the first step and shape detection in the second step. Fuzzy clustering is used as the underlying segmentation model. Defect shape and depth information after post-processing are used as input to an automated condition state assessment methodology. A simple formulation based on both the damage area and depth is then utilized to assess the condition of culverts based on a 4-point condition assessment scale. The proposed framework was demonstrated with a test example. Future research would entail consolidating the concept by extensive testing and integration for real time application.

17. Key Words Corrugated steel culvert pipe, Corrugated metal pipe, Pipe inspection and cleaning, Condition state, Pipe repair and replacement, Service life, Culvert Information Management System, Markov model, Cathodic protection, Remote monitoring unit, Impressed-current Cathodic Protection	18. Distribution Statement		
19. Security Classif (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 78	22. Price

Form DOT F 1700.7 (8-69)

Acknowledgments

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LIST OF ABBREVIATIONS AND SYMBOLS

American Association of State Highway and Transportation	AASHTO
American Society for Testing and Materials	ASTM
California Department of Transportation	Caltrans
Cathodic Protection	CP
Closed circuit television	CCTV
Condition State	CS
Corrosion Rating	CR
Corrugated Steel Culvert Pipe	CSCP
Culvert Information Management System	CIMS
Culvert Management System	CMS
Departments of Transportation	DOT
Direct Current	DC
Federal Highway Administration	FHWA
Frames per Second	FPS
Governmental Accounting Standards Bureau	GASB
Impressed Cathodic Protection	ICP
Infrastructure Information Management system	IIMS
Minnesota Department of Transportation	MnDOT
Municipal Infrastructure Management System	MIMS
National Bridge Inspection standard	NBIS
National Cooperative Highway Research Program	NCHRP
Red Green Blue format	RGB
Remote Monitoring Unit	RMU
Stress Corrosion Cracking	SCC
Tennessee Department of Transportation	TDOT
The National Corrugated Steel Pipe Association	NCSPA
The New York Department of Transportation	NYDOT
Transportation Asset Management System	TAMS
Video Home System,	VHS

SUMMARY

Although corrugated steel culvert pipe (CSCP) is widely used as an inexpensive means for crossing streams and providing drainage for roadways in many transportation systems in the US, historically, very little has been done regarding their condition assessment and planned maintenance. A four-level condition state assessment system based upon the Caltrans system was developed, including quantifiable section losses, specific surface features, and a prescribed response associated with each condition state. A Markov deterioration model was used to predict the future condition state of new CSCP in urban and rural settings. The transition probabilities were based upon inspection data and corrosion studies. The model was extended to predict the future condition of new CSCP in both settings over a 30-year life. It should be noted that the Markov model does not take into account the effects of maintenance or rehabilitation. The Markov deterioration model is presented as an appendix to this report. In the next phase of this research project a Weibull distribution was used to predict the remaining service life of CSCP and other culverts. The Weibull distribution provided better agreement with pipe corrosion data that became available subsequent to the completion of this project.

A framework for inspection and rehabilitation/replacement of CSCP was developed. This framework is expected to lead to the development of a Culvert Information Management System (CIMS), where justification and need are based on recent Governmental Accounting Standards Bureau (GASB) requirements. The CIMS will serve as a vehicle for evaluating infrastructure assets and facilitate comparing the present costs of preserving infrastructure. Benefits of the proposed system will include long-term savings that should accrue from adopting optimized preventive maintenance strategies. Within this framework the condition states of the CSCP are used to express the extent of their deterioration. Different rehabilitation options are discussed and recommendations are made for deteriorated CSCP's. These options are to be incorporated into the proposed CIMS, which uses survival probabilities based on the condition state of CSCP during the previous year. The survival probabilities for being in Condition States 1, 2 or 3 are computed based on research data on corrosion. However, implementation of the proposed CIMS requires field data for CSCP's or laboratory tests that mimic field conditions.

The proposed 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 the CSCP's needing inspection and rehabilitation/replacement. The proposed CIMS can also be used to estimate the required annual budgetary allocation for a stipulated planning

horizon to maintain or improve the aggregate condition state of the CSCP network. It also may be used to maintain or improve the total highway CSCP network asset value, thereby meeting the GASB-34 requirements. The optimum sequential path in the annual decision making process may then be determined using a combination of operations research tools.

A framework for automated-real-time monitoring of the condition of culverts based on the identification of internal defects via video inspection was also developed. Manual inspection using closed circuit television has several drawbacks, such as inconsistency and subjectivity due to human evaluation. Analysis of digital video, which consists of thousands of megabytes even at lower resolutions, can be a laborious task not suited for real time implementation. An innovative approach was developed in which image frames are judiciously extracted from the video and analyzed to locate and categorize major defects. Instead of analyzing all the extracted frames, several consecutive frames can be skipped with minimal loss of accuracy, resulting in considerable savings in memory and system requirements. Each frame is preprocessed to enhance contrast using an adaptive scheme and to reduce dimensionality in pixel-space by implementing region based processing. The preprocessing is followed by a two-step image segmentation process, which implements a background elimination procedure in the first step and shape detection in the second step. Fuzzy clustering is used as the underlying segmentation model. Defect shape and depth information after post-processing are used as input to an automated condition state assessment methodology. A simple formulation based on both the damage area and depth is then utilized to assess the condition of culverts based on a 4-point condition assessment scale. The proposed framework is demonstrated with a test example. Future research would entail consolidating the concept by extensive testing and integration for real time application.

RESEARCH OBJECTIVES

The primary objective of this research was to develop a comprehensive preventive maintenance program for CSCP's that would be implemented by a CIMS and enable NJDOT to be proactive in preventing culvert failures instead of just reacting to failures. Secondary objectives in order to implement such a preventive maintenance system are:

1. To develop guidelines for inventorying, inspecting and cleaning CSCP's.
2. To develop guidelines for assessing the condition of CSCP, predicting and estimating service life and determining appropriate corrective action.
3. To determine the best methods to repair, rehabilitate and replace CSCP's.
4. To develop guidelines for record keeping and data storage for inspection and maintenance.
5. To estimate the cost of the statewide preventive maintenance program.

INTRODUCTION

CSCP's serve as an inexpensive means for crossing streams and providing drainage along and across roadways, and thus are very important components of many transportation systems. CSCP's are cheaper, more easily transported, and more easily assembled than other culvert pipes. The design flexibility of CSCP and its predictable mechanical properties allow the engineer to design a culvert, which will withstand heavy traffic loads and other site conditions that might occur during the life of the pipe. Field inspections have confirmed the durability and economy of CSCP time and time again.

Since its introduction to the construction industry, CSCP has had many revisions to the basic composition, corrugation pattern, and coating. Many state departments of transportation and independent engineering firms have conducted numerous durability studies to determine the life expectation of CSCP. Based on previous works performed by the Corrugated Steel Pipe Institute, the life expectancy of CSCP is expected to be in excess of 100 years. However, as with other pipe materials, corrosion protection is required for steel pipes to achieve their full-expected life. The coating for CSCP may be zinc-coated steel; aluminum coated steel; zinc-aluminum coated steel; bituminous-coated; and epoxy coated.

According to NJDOT, CSCP has been widely used in New Jersey for many years, both alongside and under roadways. Most CSCP that has been in place for 30 or more years has become deteriorated, especially at inverts. Corrosion and abrasion are the major causes of CSCP deterioration. Corrosion is a significant problem for underwater structures, particularly in environments where there are conditions that accelerate the process. Three dominant factors that cause deterioration of CSCP are soil chemistry, water chemistry, and abrasion resistance of sediments. The abrasion potential of an environment can be evaluated by measuring the slope of installation, the velocity of the flow, and the size of the abrasive materials in the culvert. Erosion of CSCP at the inverts can mechanically damage the invert surface.

NJDOT Maintenance has identified deterioration of CSCP as a significant problem because many installed pipes are at or near the 30-year age mark. Most of these older culverts that are currently in the field exhibit 80-90% section losses, or in many cases 100% section losses at the inverts of the culvert. If this deterioration is not addressed within the next several years, many areas will exhibit soil transfer from under the pipe resulting in erosion and/or collapse. A pipe collapse may result in the above roadway settling, or itself collapsing, which would prove very costly in terms of traffic delays and roadway repair. Listed below are general types of culvert problems.

Serviceability-related problems:
- Scour and erosion of streambed and embankments

- Inadequate flow capacity
- Corrosion and abrasion of metal culverts
- Abrasion and deterioration of concrete and masonry culverts
- Sedimentation and blockage by debris
- Separation and/or drop-off of sections of modular culverts
- Inadequate length

Strength-related problems:
- Cracking of rigid culverts
- Undermining and loss of structural support
- Loss of the invert of culverts due to corrosion or abrasion
- Over-deflection and shape deformation of flexible culverts
- Stress cracking of plastic culverts

Culverts are susceptible to internal and external corrosion once they are placed in the ground. Corrosion is an electrochemical phenomenon where a metal tends to return to its oxide state. An electrical current flows from the metal through ions in the surrounding water or soil. The resistivity of a given soil or water is the simplest criterion for estimating its relative corrosiveness and defines its ability to serve as an electrolyte to conduct current. Values lower than 3,000 Ω.cm are considered corrosive, and those less than 1,000 Ω.cm are seen as very corrosive.

Other factors that affect resistivity include soil moisture content and soil compactness. Since resistivity is a function of temperature, frozen soils and water are much less corrosive than in their unfrozen state (Gory, 1998). Sandy soils that easily draw water away are non-corrosive; clay-like soils that hold water have low resistivity and are corrosive (Gory, 1998). Additional environmental factors that play a significant role in corrosion are pH, oxygen level, acidity level, and chloride and sulfate levels.

CSCP failures by wall thinning initiated at the inverts are mostly due to erosion and internal corrosion. There are many kinds of corrosion mechanisms:
- **Stress Corrosion Cracking** (SCC) is the cracking induced from the combined influence of stress and corrosive medium. The impact of SCC on a material usually falls between dry cracking and the fatigue threshold of the material. The required stresses may be in the form of directly applied stresses or in the form of residual stresses. Cold deformation and forming, welding, heat treatment, machining and grinding can introduce residual stresses. The magnitude and importance of such stresses is often underestimated. SCC may be initiated at a point where the passive film is destroyed possibly due to erosion. Stress concentrations may tend to localize such defects. SCC may also propagate by the dissolution at a crack tip. If the film provides poor protection one would get uniform corrosion rather than localized, so SCC should occur only if the corrosion resistance is low. A material showing high SCC resistance in certain

media may not show it in others. Any material can have a range of environments in which SCC occurs (Kowaka, 1990).

- **Corrosion Fatigue** can be defined as the type of failure, which occurs when a component is subjected to cyclic stressing in a medium, which is able to attack the material continuously if it becomes chemically exposed (Shreir, 1994). Corrosion fatigue occurs in both corrosive medium (e.g. chemical material transported by pipes in most chemical plants) and non-corrosive media (e.g. fresh water as in the case of CSCP). Many metals are resistant to corrosion in normal atmospheric conditions, owing to the presence of coherent surface oxide film through which participants in the corrosion reaction are unable to diffuse. But if the stress in the specimen causes damage to the film; it ceases to protect. As fresh metal is exposed the medium becomes capable of attack in these circumstances (Shreir, 1994).

- **Graphitization** corrosion is the selective leaching of iron metal, leaving behind a porous matrix of carbon, voids, and hydroxide corrosion products. Graphitization results from the different levels of galvanic activity between two elements in an alloy. Cast iron, a common pipeline material, is particularly susceptible to this kind of corrosion (Smith et al, 2000).

- **Tuberculation** is the development of a crustaceous layer (tubercules) and results in obstruction of the pipe interior thereby reducing carrying capacity. Biological activity associated with tuberculation may accelerate the corrosion process.

- **Pitting Corrosion** is a localized form of corrosion by which cavities or "holes" are produced in the material. Pitting is considered to be more dangerous than uniform corrosion damage because it is more difficult to detect, predict, and design against. Corrosion products often cover the pits. The pits gradually get deeper until ultimately they break through the wall of the pipe. Hence a small, narrow pit with minimal overall metal loss can lead to the failure of an entire engineering system. Pitting corrosion, which, for example, is almost a common denominator of all types of localized corrosion attack, may assume different shapes. Apart from the localized loss of thickness, corrosion pits can also be harmful by acting as stress risers. Fatigue and stress corrosion cracking may initiate at the base of corrosion pits (Fontana, 1986 and Dillon 1982).

Durability of CSCP

Durability is important for design and construction and hence durability is evaluated from field evaluation studies. In conjunction with the manufacturing developments, several State Highway Departments and engineers of other agencies have conducted numerous durability studies to determine the life expectancy of corrugated steel pipe. The Ohio Department of Transportation, which covered an 11-year period where 1,616 culverts were inspected, conducted a thorough study (Beaton and Stratfull, 1962). They developed a chart to predict metal loss for CSCP's. For an example, a 16 gage CSCP in a neutral

(pH = 7.0) environment would have a predicted life of 20 years if complete perforation of the metal is allowed. Structural adequacy of the reduced wall was not addressed. The general consensus of the above studies was that CSCP has a life expectancy of 10 years to about 35 years before perforation of the metal occurs. This forced the industry to seek a solution to extend the service life, via coatings both applied and bonded.

There were additional durability studies conducted by several DOT's to extend the service life of CSCP's by corrosion mitigation. These studies typically considered deterioration from the inside of the metal pipe and ignored deterioration from the soil-side. Applied coatings refer to any material that is applied to the pipe after the base metal has been either zinc galvanized or cladded with aluminum. The applied coatings can be sprayed, painted, dipped, or adhered either before or after fabrication. Bituminous, or asphalt coatings, are the most commonly used applied coatings. Now nearly all the State Departments of Transportation use minimum design service life values of 50-75 years for coated or protected CSCP's [Rinkler Materials, 2003].

The technology transfer center at the University of New Hampshire finds that CSCP are subject to corrosion and abrasion, and have a shorter life span than other materials [DiBiaso, 1996]. Applied coatings (bituminous, asphaltic, etc.) do not improve the hydraulic characteristics of corrugated steel pipe. According to a Missouri DOT Durability Report (MR87-1), "coatings such as bituminous or polymer materials cannot be used to lower the coefficient of roughness for CSCP because the coating will be lost first, leaving the hydraulic conditions controlled by the uncoated CSCP".

The California Division of Highways conducted a comprehensive field study, in which over 7,000 CSCP's were evaluated by specially trained personnel. It concluded that pH and conductivity of soil and water were the most important factors influencing the durability of CSCP [Beaton and Stratful, 1962]. Curves were developed based on this information.

After nearly 90 years of practical experience with CSCP installations, the pipe has a proven durability for use as culverts and storm drains. CSCP can be designed for field conditions by using galvanizing, asphalt coating, paved inverts, and varying the metal thickness [CSPI, 1990].

INSPECTION AND CLEANING of CSCP

Inspection and Inventorying

The assessment of CSCP is a difficult exercise because culverts are usually substructures, submerged, or placed in a remote location, thereby making inspection difficult. In order to determine whether a culvert requires repair,

rehabilitation, or replacement, a comprehensive inspection needs to be carried out, and the report of such inspection properly documented.

In the late 1970s and 1980s, several CSCP's collapsed without any apparent warning (Moore et al., 1985). A number of state Departments of Transportation and Road Authorities became increasingly worried about the stability and durability of culverts and therefore proposed and started the implementation of visual inspection programs, which involved a complete inventory and appraisal of all CSCP's in their states.

Culvert inspections should be scheduled on a regular basis to ensure that culverts are functioning properly. Presently, there is no standard or consistent methodology to inventory, inspect, and evaluate culverts in the field. Inspection of culverts is very important in a culvert maintenance program. In order to ensure a successful culvert inspection program, established standard guidelines must be put into place that all inspectors follow so that the data obtained are consistently collected. Table 1 show a typical suggested data form. 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 inspections lack consistency because they are carried out by multiple inspectors with differing biases.

According to Ring (1984), culvert inspection scheduling is a function of the culvert size, the environment in which the culvert is placed, and the characteristics of the soil and the backfill. For example, in locations where there is acidic run off or industrial discharge, inspections should be carried out at more frequent intervals than for less harsh environments. Ring (1984) also recommended that major pipes be inspected at least every 3 years and more often where conditions are harsh. A comprehensive Culvert Inspection Manual was developed by the Federal Highway Administration (FHWA) that detailed the inspection procedures, guidelines and inspection frequency. FHWA required that inspections be performed once every 2 years rather than every 3 years (Arnoult, 1986).

Our literature search revealed that most departments of transportation and road authorities consider the following factors during a culvert inspection:
- Hydraulic capacity
- Soil conditions
- Joint failures
- Corrosion
- Wall thickness
- Deformation near the ends of the culvert

Each of these factors is graded on a scale of 10.

Table 1: A Typical Suggested Data Page

LOCATION							
County	③	Division		District	②	Culvert Number	⑧
Route	⑤⑦	Milepost	⑪	Located _____ miles ⑨ from		Over	⑥

APPROACH ROAD				
Left shoulder width	Roadway width	Median width	Right shoulder width	Total ㉒

ROAD OVER CULVERT				
Left sidewalk width ㊿	Left shoulder width	Roadway width ㊳	Median ㉝ None Open Closed	
Median width ㊱	Right shoulder width	Right sidewalk ㊿	Total cross ㊲ section width	Number of lanes ㉖ on culvert

CULVERT					
Shape	Material ㊸	Coating Type/ Cathodic Protection		Skew ㉞	Length along ㊾ roadway ₵
Barrel size ㊽	Barrel length	Number of ㊺ barrels	Type of end treatment		Depth of cover

UNDER CLEARANCE					
Left	�55	Vertical	�54	Right	�56

MISCELLANEOUS					
Bypass length ⑲	Federal Aid ㉔ System	Functional ㉖ Classification	Year built ㉗	FA project number ㉓	
ADT ㉙	ADT year ㉚	Design load ㉛	Culvert status Open, Closed, Posted		

☐ SI & A Item Numbers

(BACK)

HYDRAULICS		
	DRAINAGE AREA	DESIGN STORM FREQUENCY
	DESIGN DISCHARGE 'Q'	HEAD WATER ELEVATION

SKETCH OF CULVERT

PLAN VIEW	CROSS SECTION

8

The reporting system features suggested by Arnoult, 1986 are:
- Inventory data
- A structure file
- Procedure for planning and scheduling inspection
- A system for recording the inspection results
- A system for updating the structure files.

NCHRP Synthesis 303 on "Assessment and Rehabilitation of Existing Culverts" also documents the following methods for inventorying, inspecting, and cleaning CSCP:

1. There is a need to establish a standard set of guidelines, under which all inspectors will inspect and will consistently collect data.
2. NYSDOT and Connecticut DOT have comprehensive culvert inventory and inspection manuals that describe their culvert management program.
3. Most agencies clean their large diameter culverts at between 2 – 3 year intervals.
4. There is a need for a regular inspection schedule, similar to that provided in the National Bridge Inspection Standard [NBIS, 2002]. However, there is no regular cycle being followed by most transportation agencies.

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 the benefits that were being derived.

The FHWA developed a two-volume guide for highway agencies on procedures that may be used to repair a wide variety of types of problems that beset metal and concrete culverts of all types. Volume I contains information on culvert materials, shapes, construction, problem identification (including hydraulic capacity), maintenance, retrofitting, repair, and replacement. Volume II consists of appendices on standards, repair and retrofit procedures, specifications, and an annotated bibliography [Ballinger and Drake, 1995]. It suggests there are three types of inspection programs that may be undertaken:

1. A program that is an extension of the National Bridge Inspection Program;
2. A program that focuses specifically on culverts as described in the Culvert Inspection Manual (Arnoult, 1986); or
3. One that is conducted during periods of scheduled maintenance.

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 (FHWA, 1995). Apart from the visual method of inspection adopted by most state departments of transportation and road authorities, other forms of inspecting culverts are closed circuit TV and still photos.

NJIT proposed a new inspection frequency for CSCP's in NJ that is shown in Table 2. This table should only be used if the proposed Phase II of the Culvert Information Management System (CIMS) described later is not implemented. The table categorizes culverts into three categories based on the following factors: 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.

TABLE 2: Proposed CSCP 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 CSCP's	FHWA Guidelines	Reported problems
BASIS FOR LEVEL Physiological Features:	Free of corrosion and debris	Evidence of corrosion and/or debris	Reported clogging or collapse
SEDIMENT	Low Abrasion-Minor bedloads of sand and gravel $V < 1.5$ m/s	Moderate Abrasion-Average 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:	10 yrs	15 yrs	30 yrs (Design Life)

Based on the selection criteria in Table 2 one can select the most stringent inspection schedule. For example, all large diameter CSCP's crossing major

highways should be by default in Category II or III. Based on the literature search, it was difficult 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 CSCP and examining the surrounding soil. If it is gravelly, select a high value; sandy, select a 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 2.

Culvert Video Inspection

Closed circuit television (CCTV) surveys are typically conducted using a remotely controlled robotic vehicle carrying a television camera through the culvert. Typically, the inspection camera is directly hooked onto an image processing center, and transmits real time video images to an operator in a mobile unit connected to cameras and the crawler mechanism. The videos are converted to digital mpeg files, and the corresponding identifying information is entered by the operator. The software prompts the operator to enter damage location, a descriptive account of the damage and assign a corresponding severity number. The software then provides detailed graphical and summary reports of the damage. The involvement of the operator makes the system vulnerable to lapses in operator concentration, inexperience and subjectivity. Additionally, in many cases, the lighting conditions are insufficient to provide the operator with a clear picture of the state of the culvert. References can be found in the literature where various researchers have developed techniques to automate the process of locating defects in pipelines (Sinha, 2004, 2003, 2002, 1999; Fieguth, 1999; Moselhi, 1999; Broadhurst, 1996). However, manual intervention does not end at the defect identification level; more subjectivity enters in when condition states (or ratings) are assigned to the culvert based on the observed level and severity of the damage. Not only is an automated fault diagnosis system needed to identify and locate damage, but an automated condition state assessment system is also needed to augment it.

Another way of culvert inspection is real-time-automated monitoring of the condition of culverts based on the identification of internal defects via video inspection. Manual inspection using closed circuit television has several drawbacks, such as inconsistency and subjectivity due to human evaluation. Analysis of digital video, which consists of thousands of megabytes even at lower resolutions, can be a laborious task not suited for real time implementation. An innovative approach is to judiciously extract image frames from the video and analyze the frames to locate and categorize major defects. Instead of analyzing all of the extracted frames, several consecutive frames can be skipped with minimal loss of accuracy, resulting in considerable savings in memory and system requirements. Each frame is preprocessed to enhance contrast using an adaptive scheme and to reduce dimensionality in pixel-space by implementing region-based processing. The preprocessing is followed by a two-step image

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segmentation process, which implements a background elimination procedure in the first step and shape detection in the second step. Fuzzy clustering is used as the underlying segmentation model. Defect shape and depth information after post-processing are used as input to an automated condition state assessment methodology. A simple formulation based on both the damage area and depth is then utilized to assess the condition of culverts based on a 4-point condition assessment scale.

Image Analysis

Monitoring structural integrity of culverts is essential to timely implementation of maintenance and rehabilitation tasks. CCTV inspection data provide general information about the state of the culvert compared to information obtained using specialized inspection techniques that use acoustic, magnetic and electrical property changes in the culverts to ascertain and pinpoint damage locations. CCTV inspection output in the form of videotapes, both analog and digital, provide a visual verification of the presence of damage. Internal damage in culverts is usually in the form of random shaped cracks, holes, etc. A number of pattern recognition and image processing methods have been proposed in the literature, and almost all of these are based either on edge detection methods or mathematical morphology analysis, or a hybrid method of these two approaches (Sinha, 2002). A neural network based approach for image processing, image segmentation and feature extraction is presented in (Moselhi, 1999), and recently, a neuro-fuzzy classification algorithm has been proposed in (Sinha, 2004, 2003, 2002), based on the local detection of linear defect structures using a pair of simple line detectors.

The mpeg file produced by the inspection is a visual record of the interior of the culvert. The present system of manual inspection involves moving the camera to all places of the culvert, not just looking at it *straight-up* but moving it sideways and zooming-into locations where a defect has been identified by the operator. In order to automate the system, it is proposed that the camera moves in a straight line along the center of the culvert and always photographs the culvert *straight-up*. This eliminates ambiguities within frames, expedites the inspection, and results in a consistent series of images. It is also proposed that for proper installation of the completely automated system, the internal lighting conditions produced by the camera flash are consistent throughout. The present digital inspection systems record the video on a 3-plane RGB format. The mpeg format is tagged on a time scale and frames can be extracted using frame-capture software such as Pinnacle Studio® or any other appropriate software. The tagged mpeg can also be broken down into frames using the tag numbers as a frame capture criterion. For a 30 frames per second (fps) video, the Pinnacle system can extract 30 frames in a second on a real time basis and save each frame as a jpeg image. For the sake of automation, it is not advisable or practical to perform image analysis on all the extracted frames – two consecutive frames on a 30 fps

video would be almost identical, and this implies that the second frame can be neglected. A consistent methodology to skip frames is described later.

An 18 second mpeg video is analyzed using a time gap of T = 1.8 seconds to demonstrate the concept. The necessary assumptions about constant camera trajectory and speed are not fulfilled here, and hence, some manual adjustments had to be made. This however, does not affect the methodology in any way. Frames are analyzed at 1.8 second intervals; i.e., one frame in every 54 frames is analyzed. The frames are shown on a time scale in Figure 1. Each frame is an RGB image of size 960 pixels x 720 pixels. The images are first reduced in size to produce two sub-images. Hence, the two sub-images are of size 320 pixels x 360 pixels, and are located on the left and right sides of the original frame. The sub-images are tagged by a label for easy identification. The original image is identified by its position on the time scale – the first image of the series will be T0.0, followed by T1.8, and so on. The sub-images are identified as Left (L) and Right (R); this helps in easy interpretation of results. The sub-images are then converted into 8-bit grayscale images, followed by a contrast enhancement using the Ridler Calvard threshold scheme.
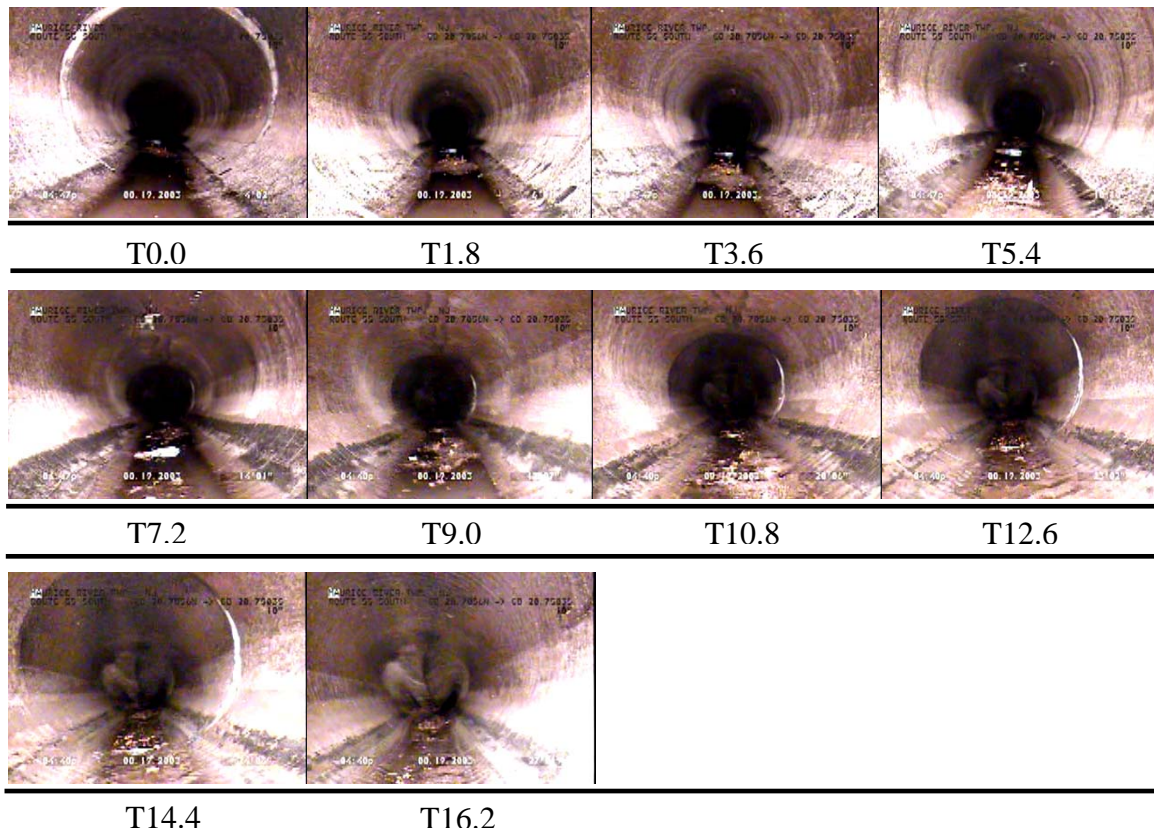

| T0.0 | T1.8 | T3.6 | T5.4 |

| T7.2 | T9.0 | T10.8 | T12.6 |

| T14.4 | T16.2 |

Figure 1: Ten Frames Analyzed With a 1.8 Second Time Gap (T = 1.8 s)

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Figure 2 shows the sub-images T1.8-L and T1.8-R and their coordinate systems, after all the preprocessing steps have been carried out. The sub-images are then divided into square blocks with a = 10, where a=n/p as shown in Figure 2. Other values of a, such as a = 20, and a = 5, were also examined, and a = 10 was found to produce better results compared to the other two. For the 320 pixel x 360 pixel sub-images, there are 1152 such 10X10 pixel square blocks. The block grayscale mean and the block grayscale standard deviation are computed within the 100 elements of each block, and the intra-block gradient is calculated. For blocks on the edges and corners of the sub-image the formula is modified during run time to count only three neighborhood blocks (for corner blocks) and five neighborhood blocks (for blocks on the edges). The sub-images are clustered and only the blocks in the foreground clusters are retained. The foreground cluster is comprised of blocks with low mean, low standard deviation, and almost equal gradient. The background blocks are discarded from future analysis. For T1.8-L and T1.8-R shown in Figure 3(a) and (b) respectively, the step 1 clustering identifies 66 and 108 foreground blocks among 1152 blocks each. These also include darker regions on the culvert surface left behind by sedimentation and water level marks. The water level mark usually produces a straight-line pattern, which can be instantly discarded from future analysis. Other marks manifest themselves as random blobs, and these are not recognized as large shape clusters in the second step of fuzzy clustering.
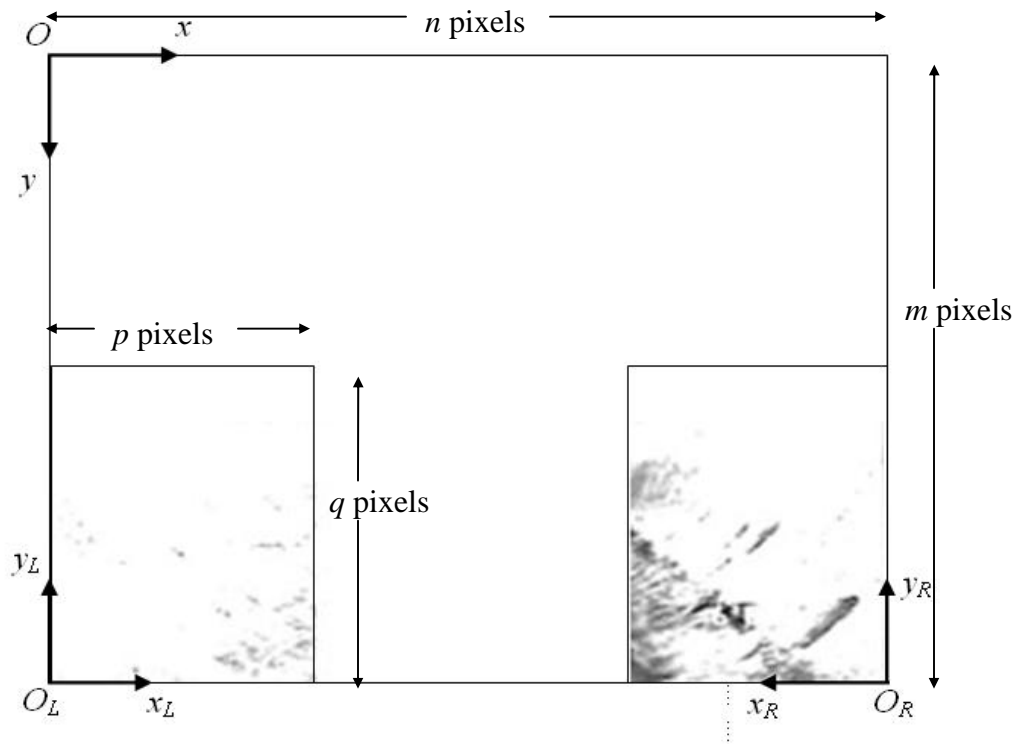
Figure 2: Left (L) and Right (R) Sub-images and Their Coordinate Systems. The frame coordinate system is shown as O (x, y).
Sample frame: T1.8, sample sub-frames: T1.8-L and T-1.8-R

(a)   **(b)**
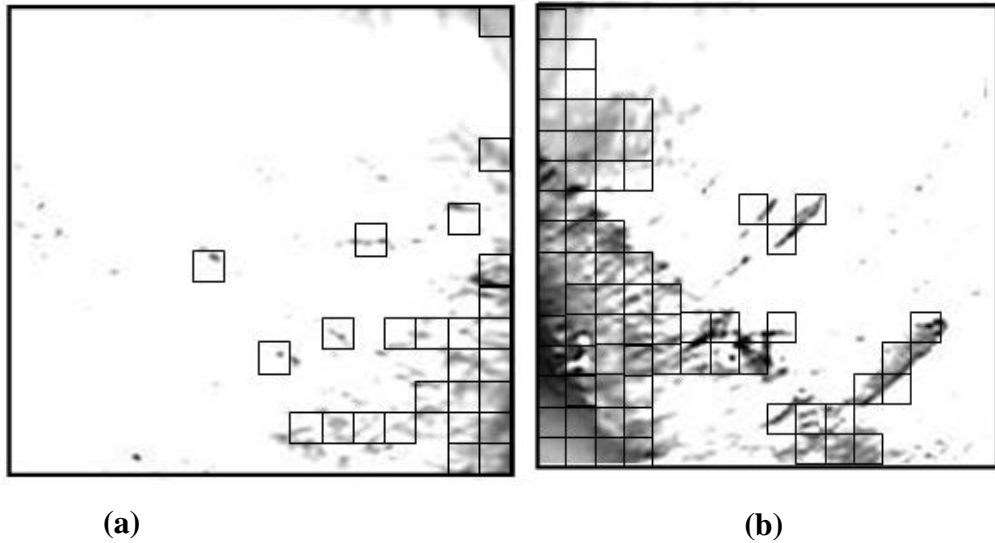
Figure 3: First Step Segmentation Results Using Fuzzy Clustering (foreground is shown as blocks, exaggerated in size) - (a) 66 foreground blocks identified in T1.8-L, (b) 108 foreground blocks in T1.8-R

In the second step, three large shape clusters are identified in T1.8-L, and five large shape clusters are identified in T1.8-R. These are verified during run time by simultaneously plotting the cluster validation measures, and are shown in Figures 4(a) and (b). A snapshot of the database created after image segmentation and classification is shown in Table 3. The defects are labeled as T1.8-L-01, T1.8-L-02, and so on.

(a)   **(b)**

Figure 4: Classification of Defect Shapes Based on Fuzzy Clustering – (a) three defects identified in T1.8-L, and (b) five defects identified in T1.8-R

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Table 3: Snapshot of the Database with Corrected (Scaled) Defect Area in Pixel^2 and Depth Severity Information

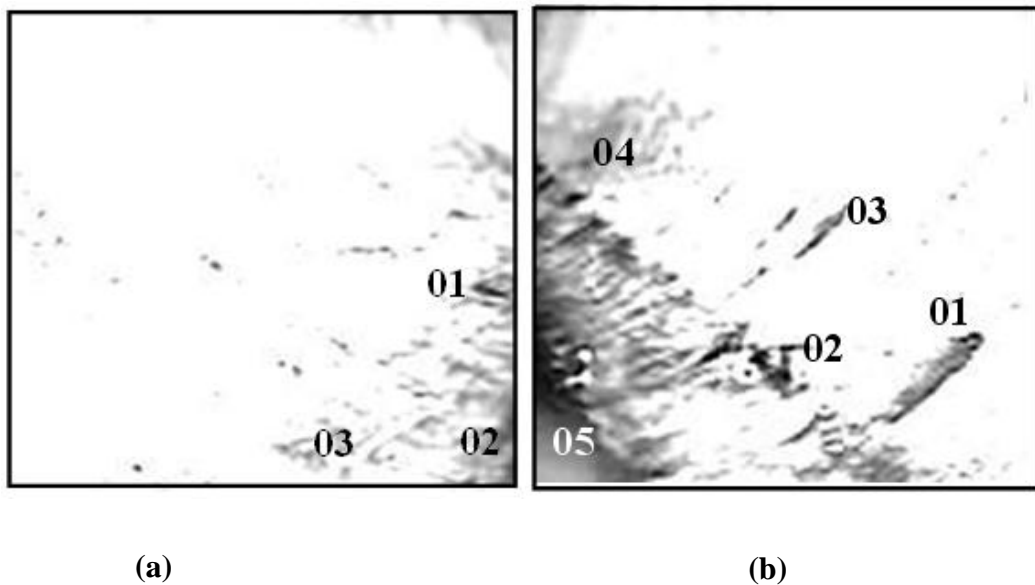| Defect ID	Surface Area (pixel^2 x 10^3)	Mean Location X	Mean Location Y	Scaling factor	Corrected area (pixel^2 x 10^3)	Smallest Gray value (mean)	Depth Severity 1 = Deep 0 = Shallow
T0.0-R-0X							
T1.8-L-01	10.5	271	145	1.85	19.39	0	1
T1.8-L-02	6.2	282	36	1.88	11.66	12	0
T1.8-L-03	3.9	221	41	1.69	6.59	15	0
T1.8-R-01	19	95	105	1.30	24.64	0	1
T1.8-R-02	12.9	215	112	1.67	21.57	0	1
T1.8-R-03	8.1	172	175	1.54	12.45	0	1
T1.8-R-04	21.8	282	245	1.88	41.01	27	0
T1.8 R-05	39.2	305	92	1.95	76.56	17	0
T3.6-L-01							

Characteristics such as size, location, and mean of the 10 darkest center pixels, are stored in the database. An appropriate scaling factor is used to correct for perspective, and another factor is used to correlate surface area in pixel^2 to surface area in cm^2 or inch^2 (not shown in the database). The two factors can also be combined into one. While the perspective correction factor depends on the location, the correlation factor is a constant. The perspective correction factor (labeled "scaling factor", column 4 in the database) depends only on the mean x-location of the defect. For a shape near the outside edges of the sub-image, the scaling should be less intense, but a defect shape near the inside edge is more compressed (due to perspective), and hence requires a larger scaling.   If $x(m)$ denotes the mean x-location of the defect, the scaling factor is defined as shown below, where p value is defined in Figure 2.

$$SF = \frac{x(m)}{p} + 1 \qquad (1)$$

The exact determination of these factors is out of the scope of this work, but has been conceptually explained and studied. Experiments and learning algorithms can be used to specify and implement suitable correction and correlation factors. Also the false positives defined as the faulty categorization of discoloration, sediment deposits, or debris, as deterioration, would require validating the image analysis results using field test data. As part of the future work, a surrogate pipe will be used for such validation. The identification of false positives (or false negatives) will also depend on the tuning of the algorithm, especially how the de-fuzzification part (identifying valid number of clusters from the clustering algorithm) is constructed and analyzed. For reasons understandable, the algorithm should tend more towards identifying false positives (since there can never be perfect tuning under real world conditions), than having it tuned towards a false negatives approach. This is however a matter of policy, depending on how proactive the maintenance agency desires to be.

Culvert Cleaning

Various equipment and methods are commercially available today for cleaning culverts. The type of equipment and method to be used depends on the degree of movement and versatility required. As part of the cleaning operation, some agencies also provide video inspection of a problematic section or entire system. The video inspection systems can also locate 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 culvert from debris and retain normal flow of water. Table 4 provides a list of all the available methods for CSCP cleaning with the advantages and disadvantages of each method.

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 (20ft)
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.
Compressed Air Jet	Effective in removing debris from vertical walls	Normal working depth limited to 20m (66ft).
Fire Hose Flushing	Effective in removing light materials from the wall and for general removal of light materials	Limited 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.

Vacuum Pumps are generally mounted on vehicles and are used to remove sediments from pipes. It requires a 760-1200 liter (200-315 gallons) holding tank, and the vacuum pump has a 250-mm (10 inches) diameter flexible hose with a serrated metal end for breaking up caked sediments. This system can remove stones, bricks, leaves, litter, and sediment deposits at a depth of 0 to 6 meters (20ft) below ground.

Water Jet Spray is also mounted on a vehicle and requires a pressure pump and a 760 to 1200 liter (200-315 gallons) water supply tank. Because of the energy supplied from the water jet, this equipment cannot be used to clean trench walls that are subject to erosion.

Compressed Air Jet is used to clean and remove debris from vertical wells. It requires a holding tank (partially filled) for the water and the removed debris, a source of water supply (where the well is above the groundwater level), an air compressor (injected through a nozzle at the bottom of the well), two air lines, a diffusion chamber, and a pipe to carry the silty water and other debris to the surface. It normally works at a depth of 0 to 20 m (66ft).

Fire Hose Flushing consists of various fittings that can be placed at the end of a fire hose such as rotating nozzles and rotating cutters. The equipment cleanses the pipe while it passes through it. The exhausting water jet is very effective in removing material from walls.

Sewer Jet Flushes is usually truck-mounted and consist of large water tank of at least 3800 liters (1000 gallons), a triple action water pump capable of producing high pressures, a gasoline motor to run the pump, and a hose reel large enough for a 150 mm (6 inch) inside diameter high pressure hose. This equipment can be used for cleaning areas with grease problems, sand and gravel infiltration, and general cleaning. The use of jetting pumps capable of pressures of up to 15,000 kPa (2175 psi) and flow rates of 10 liters per second (2.6 gallons/sec) is the most popular cleaning method adopted by several state DOT's. This technique can clean the dirtiest culvert.

CONDITION ASSESSMENT AND ESTIMATION OF SERVICE LIFE

The stability of buried CSCP's depends on a number of factors including the overall geometry of the culvert; the material properties of the culvert; the geometric properties of the embankment; the material properties of the soil-culvert structure interface; and the magnitude and distribution of the earth loads transmitted to the culvert structure (Moore, et al 1985)

The prediction of culvert durability is difficult because of the number of variables in the natural environment that affect culvert service life. Many variables are easy to measure (e.g. pH, resistivity, and water chemistry), while others are difficult to measure (e.g. abrasion). The easily measurable factors also vary widely along the length of the culvert. However, culvert deterioration can be evaluated by taking into consideration the erosion rate plus chemical analyses of soils, stagnant water and test coupons of the CSCP.

The California Department of Transportation (Caltrans) surveyed the condition of pipes at hundreds of locations and developed a method to estimate CSCP maintenance free service life based on the pH and resistivity of the surrounding soil. A design chart derived from this work is shown in Figure 5, Page 19 (Caltrans, 2003). Subsequent investigations in the states of Florida, Louisiana, Idaho, Georgia, Nebraska, and Kansas showed that the Caltrans method was too conservative compared to their actual service experience. Conversely, studies in the northeast and northwest regions of the United States indicated that the method appears to be too liberal in those regions.

The Caltrans method is used as a predictor of service life by more government agencies than the other methods, because it takes into consideration a rational basis for characterizing the aggressiveness of the various sites, and was developed from a wide range of site conditions. The method however uses only pH and resistivity to estimate the time for the first perforation to occur.

Using the Caltrans method for estimating the service life of CSCP and by knowing the minimum resistivity and the pH values of the soil, the Maintenance-Free Service Life (years to perforation) can be determined from Figure 5. This value is the estimated years to perforation for an 18 gage steel culvert having a galvanic coating of 605 g/m^2 (1.98 oz/ft^2) of zinc, in the environment represented by the test samples. A factor for each steel thickness is listed in Figure 5. To determine the years to perforation for a greater steel thickness, multiply the factor for that gage by the years.

Based on Figure 5, an estimate of the typical service life of CSCP in NJ assuming the typical soil pH value of 4.5 to 7 [Murphy and Heckman, 1995], typical water pH value of 7.25 in Plainfield, NJ [Bayer 2002], and assuming a conservative resistivity value of 3000 Ωcm is approximately 30 years. This value is consistent with the estimated service life provided by NJDOT.
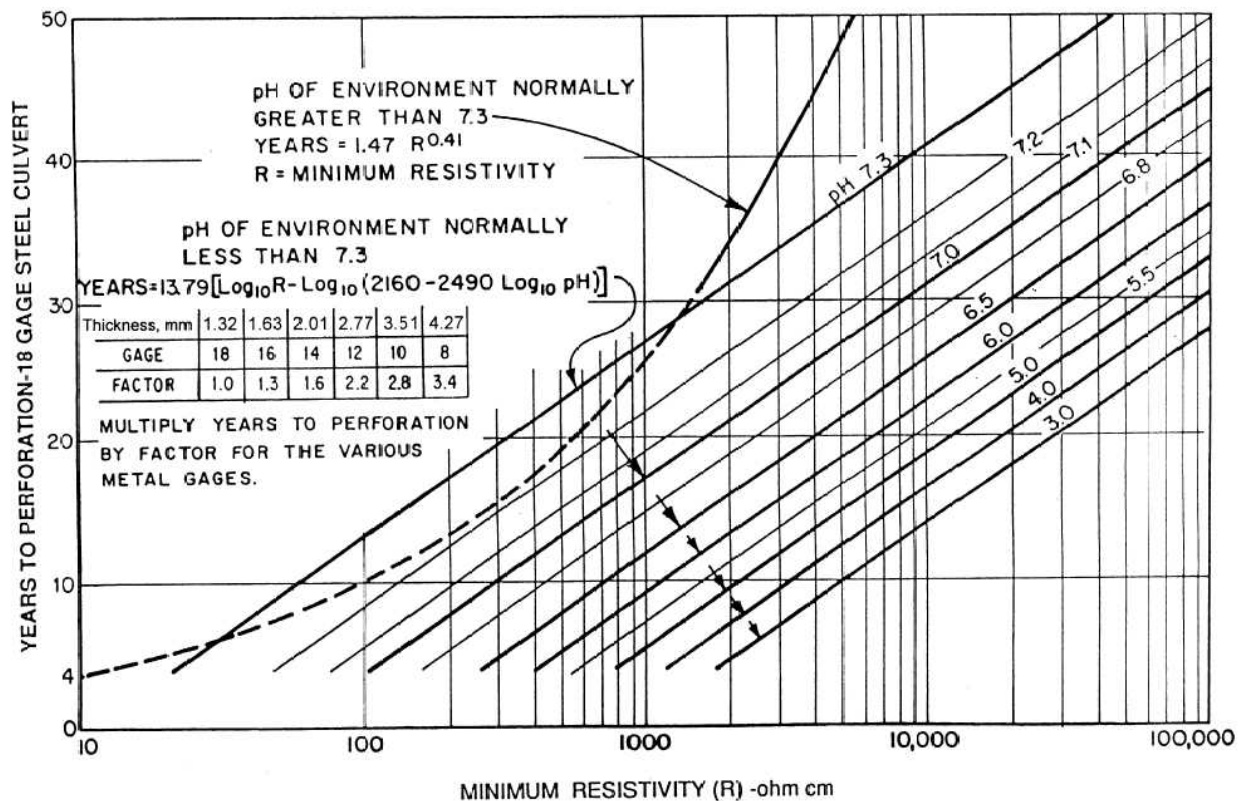

Figure 5: Design Chart for the Prediction of Service Life of CSCP (Caltrans, 2003)

The results of the various investigations illustrate the variety of conditions that can be found throughout the USA, and emphasize the need to use local information when

available. Nevertheless, the Caltrans method appears to be the most reasonable basis available for general use.

Abrasion is considered in the Caltrans method, but only to the extent that 7,000 culverts forming the database for the method are from a cross section of abrasive environments. This results in an accuracy of plus or minus 12 years in the Caltrans method. However, the accuracy can be improved if the user can calibrate the method to their applications and specific environments.

Other methods that may be used in the determining the durability or service life of culverts are those developed by the department of transportation of the following states: Florida, New York, and Colorado. In all these methods, the guideline provided an index that uses inputs of sulfate, chloride, and pH measurement of both soil and water to calculate a corrosion rating (CR) graded on a scale of 1 through 6. The advantage of the CR is that it can also be used to develop a pipe material selection table. The National Corrugated Steel Pipe Association (NCSPA) has also developed a guideline for predicting the service life of CSCP's.

The literature search also revealed that no single method considers all of the factors affecting culvert durability or precisely predicts how long a culvert can last. Therefore, a more precise method for estimating the service life of CSCP needs to be developed. However, if enough data is available on resistivity, pH, percentage of perforation, and abrasion potential, statistical methods can be employed to develop a predictive method based on the most significant criteria. Please note that there are several commercially available software modules to estimate durability of CSCP's.

Condition assessment as a process has been summarized in the following steps: (Aktan et. al 1996)
- Measure the extent of damage/deterioration.
- Determine the effect of that damage/deterioration on the condition of facility.
- Set the scale of parameters that describe the condition of the facility as a whole.
- 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. Below is a definition of condition states of painted steel girders (Sobanjo, 2001). A similarly developed rating process would also be suitable for CSCP's.
1. There is no evidence of corrosion, and the paint system is sound and functioning as intended to protect the metal surface.
2. There is little or no active corrosion. Surface corrosion has formed or is forming. The paint system may be chalking, peeling, curling or showing other evidence of paint system distress, but there is no exposure of metal.
3. Surface corrosion is prevalent. There may be exposed metal but there is no active corrosion, which is causing loss of metal section.

4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review.
5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/serviceability of the structure.

The Tennessee Department of Transportation (TDOT) uses a 10-point scale to define different condition states of culverts, which in the authors' opinion is quite complex for CSCP (TDOT 2003). Caltrans defines condition states of steel bridges and culverts, and other steel structures in terms of section loss and proposed some feasible actions as follows:

- Condition State 1: There is no evidence of active corrosion of the structure with any measurable section loss. Suggested corrective action: Do nothing.
- Condition State 2: Surface or freckled rust has formed or is forming on the structure, flaking, minor section loss less than or equal to 10% of thickness in 10% of total area. Suggested corrective action: Clean and paint and schedule an inspection.
- Condition State 3: Flaking and swelling with surface pitting but any section loss due to active corrosion is moderate and does not affect the strength or serviceability of the structure. Section loss is between 10 to 30 % of thickness in 10-30% of total area. Suggested corrective action: Clean and paint or re-lining.
- Condition State 4: Corrosion is advanced and heavy section loss to warrant analysis to ascertain the impact on the ultimate strength and/or serviceability of the structure. Section loss is greater than 30% of section thickness in over 30% of the total area. Suggested corrective action: Re-lining or replacement of structure.

With the above quantifiable section losses associated with each condition, the authors decided to recommend the condition states used by Caltrans as a starting point for NJDOT, and to predict the remaining service life of CSCP based on the above criteria. The specific details of the individual condition states may be modified as more CSCP data is accumulated.

Model for Predicting Remaining Service Life

The Markov Deterioration Model
The Markov model can be used to predict the future condition state of any system given the present state, assuming that the past states have no influence on the future state. This property is called the Markov property, and systems having this property are called Markov chains. In the Markov process, the state probabilities (probability of CSCP being in a particular state) and the transition probabilities (probability that CSCP will deteriorate to a worse state) are used to predict the future condition of the infrastructure (Deshmukh and Sanford-Bernhardt, 2000). Sobanjo, 2001 elaborated an attempt to develop a Markov deterioration model for bridges, but he used data from surveys to develop the transitional probabilities.

In order to predict the remaining service life of CSCP one needs the corrosion rate and the pipe age. Very little measured data on corrosion of CSCP was available at the time of this study. Inspection data can be used in estimating the transition probabilities for the Markov chain process, but there are very little historical data. Hence the transitional probabilities for each condition state are computed using the half-life of CSCP and the number of years it takes to deteriorate to that state. A Markov pipe deterioration model was developed and is presented in the appendix of this report on Pages 67 to 70 as excerpted from TRB Paper 04-4426. In the next phase of this research project a Weibull distribution was used to predict the remaining service life of CSCP and other culverts. The Weibull distribution provided better agreement with pipe corrosion data that became available subsequent to the completion of this project. The Weibull distribution based design service life model is presented in TRB Paper 08-1523.

Image Analysis Method for the Assessment of Condition State

When using the image analysis method, the defects identified by image analysis need to be collated to provide information about the condition state of the culvert. A simple and efficient framework is presented in this section. Techniques such as back propagation neural networks and fuzzy learning can be especially useful here because this stage involves imprecise information and absence of well-identified guidelines or documentation. A suitable learning algorithm, which models itself on known information, can be a useful tool for automation. A simple and easy to use rule-based system, which attempts to correlate the severity of the most severe defect(s) to the condition state, is presented in this research. The severity of a defect is a function of the surface area of the defect (average size) and the percentage loss of wall thickness at the defect location (average depth). The physical size of the defect can be easily calculated by using a suitable scaling and/or correction factor for perspective, which translates size information in pixels to physical size information in cm^2 or $inch^2$. However, extracting depth information from 2-D images has always been a problem. In the proposed methodology, a simple pixel grayscale mapping approach for an effective and quick approximation of the average depth at these defect locations is proposed.

The underlying assumption in this approach is that depth is manifested as darker-than-usual pixels in the image when compared with those of the boundary. A dark pixel could be the result of several other factors – improper light conditions, a black patch left by sediments or the flow, previous repair patch-work, etc. However, if the shapes are identified close to the edges of the frame and are categorized as "defects", then dark pixels along the center of the defect can be attributed to the depth of the defect. A well documented study characterizing actual depth of a defect and corresponding gray-values on the image needs to be done before the theory can be used practically. This is however beyond the scope of the present study and is a topic of future research, which will be discussed later. For the proposed methodology, it is assumed that such a well documented depth to pixel grayscale relationship exists.

The exact physical depth of a defect (in inches) is not critical at this stage of model development – the methodology relies on identifying linguistic labels for defects. A dichotomous labeling scheme would have been the simplest, i.e., one that labels defects as deep and not-deep. However, a more detailed 6-tier depth labeling system – gray-value between 0-5 is defined as *very deep*, 5-10 *deep*, 10-15 *not too deep*, 15-20 *not too shallow,* 20-25 *shallow* and greater than 25 *very shallow*-is presented in this research. A quantitative scale may be developed in future research. The average gray-value in and around the center of the defect is a direct indicator of the depth. The average gray-value of the 10 darkest pixels in a 5 x 5 pixel block centered on the mean x-, y- location of a defect is used in this study.

For every identified defect, a database is created, which stores the linguistic depth information and the surface area in cm^2 or $inch^2$. The database can then be consolidated after all relevant images have been analyzed and segmented, and all defects identified. Frames extracted from the video need to be skipped in an organized manner so as to avoid finding the same defects over and over again. The segmentation procedure lends itself well to identifying defects near the periphery of the image where they are readily apparent both to the naked eye (of the operator), and to the automation process (of the proposed methodology). The size of the retained sub-image is a parameter that can be used to determine the number of frames to be skipped. The motivation is that defects should not be identified more than once. Hence, the next frame to be analyzed should not contain any part of the preceding sub-images. This time gap can be easily approximated if the assumptions that the camera moves in a straight line with a constant speed, indeed hold true. Let the time gap between successive non-overlapping frames be T seconds, and if the camera captures the video at 30 fps, then the number of frames to be skipped between analyses is (30 times T)-1. After skipping, the next non-overlapping frame can then be analyzed, and the process repeated until the end of the culvert is reached. A more comprehensive (and more conservative approach) would be to analyze a few frames that produce *almost* similar sub-images; e.g., analyze 10 successive frames within the 30T frame interval. This provides a method to verify and consolidate the results of image segmentation, because these 10 successive frames, more or less, look at the same part of the culvert. In the next section, the results of the quick and less conservative approach are presented. Once all the defects are located (with no defect identified more than once, and no defect overlooked), the database is complete. The database can be analyzed in many different ways – in the proposed methodology, a simple rule-based analysis is used. Condition states based on a 4-point scale, i.e., 1 through 4, are defined. The definitions are given below, with emphasis on Repair, Rehabilitation or Replacement (R^3) actions,

Condition State 1: There is no evidence of section loss or loss of structural integrity and the suggested corrective action would be to do nothing.

Condition State 2: Minor section loss is less than or equal to 10% of total internal surface area. Structural integrity not compromised and the suggested corrective action would be to clean and paint plus schedule another inspection.

Condition State 3: Moderate section loss is between 10 to 30% of the total internal surface area with appreciable deterioration and the suggested corrective action would be to make a quick decision to clean and paint or repair/rehabilitate.

Condition State 4: Heavy section loss is greater than 30% of the total internal surface area or structural integrity compromised, and the suggested corrective action would be to implement R^3 immediately.

The surface area and depth information are treated separately for reasons of simplicity. The total internal surface area of the culvert is calculated, based on length and internal diameter. This is then compared to the total surface area of all defects combined together. If *S* is the total internal surface area of the culvert, and S_d is the internal area covered by defects, the surface area ratio is defined as,

$$R = \frac{S_d}{S} \qquad\qquad\qquad (2)$$

An R value less than 0.01 is considered Condition State 1; between 0.01 and 0.1 Condition, State 2; between 0.1 and .3, Condition State 3; and greater than .3, Condition State 4 (Meegoda et al., 2004 and 2005). This rating scheme can then be modified if depth labels are known. This is done by using additional information about the number of defects that fall into either *very deep*, *deep* or *not too deep* types. If all the defects are either *very shallow*, *shallow* or *not too shallow*, then the above condition state scheme can be used in its original form, with the contingency that shallow defects (in their present form) are not a threat to the structural integrity of the culvert. In other words, the surface area of defects is more important than the depth if all the defects are shallow. By shallow, it is assumed that all the three types – *very shallow*, *shallow* and *not too shallow* are included. However, the condition ratings need to be modified if some of the defects identified are deep. The flowchart in Figure 6, next page, illustrates a conceptual aggregated methodology for determining pipe condition state based on surface area and depth of defects.
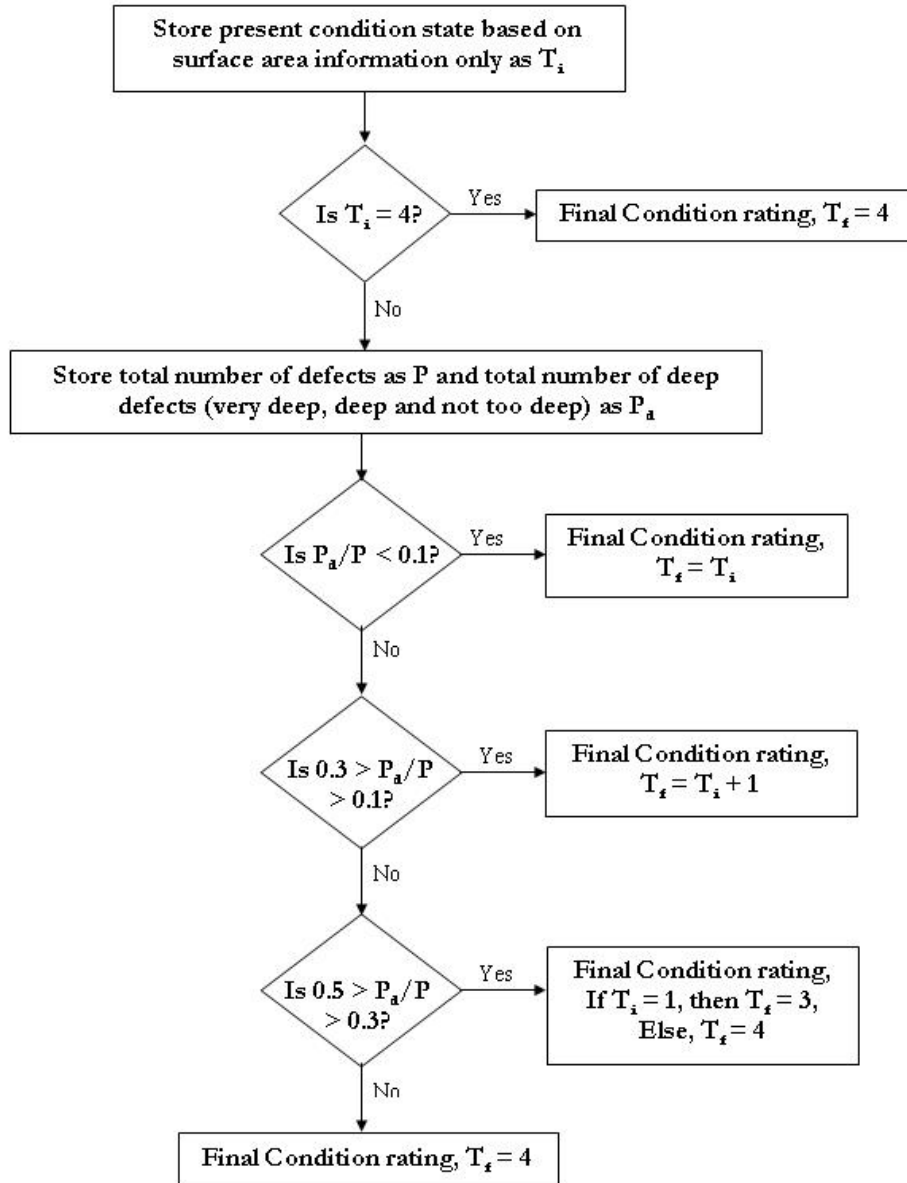
Figure 6: Combining Depth and Surface Area Information to Obtain Final Condition State Rating

CULVERT INFORMATION MANAGEMENT SYSTEM (CIMS)

Guidelines for Record Keeping and Data Storage

The literature search revealed that most state departments of transportation do not follow up with the data collected by the inspectors. It is necessary that data collected over the years should be transferred to a centralized database, and the hard copy reports should be kept for future use.

A study conducted in 2002 by the Montana Department of Transportation revealed that out of 20 states that responded in the survey; 11 states have Culvert Service Life Guidelines. In another study NCHRP surveyed several state DOT's and other agencies in order to determine current inspection programs, inventory systems, record keeping, pipe management and rehabilitation guidelines, and pipe service guidelines [NCHRP 2002]. The results from the NCHRP study revealed that guidelines for pipe assessment vary from none to comprehensive systems, or from a single page to a fully documented system. The Pennsylvania, California, Minnesota, and North Carolina DOT's and the Harford County (Maryland) Department of public works have one-page forms for collecting CSCP data. The Connecticut, Maine, and New York State DOT's and the Maryland State Highway Administration have more extensive CSCP management programs [NCHRP 2002].

The NCHRP survey identified an extensive transportation management system implemented by Maine's DOT. Their program presently supplies its data to a centralized pipe database that can be accessed from headquarters over their computer network. This database is being proposed as a data subset in the Maine DOT's data warehouse, which is under development. The ultimate goal of this project is to make the data warehouse the major data source for their transportation management system, which is called the Transportation Integrated Network Information System. This system would allow management and maintenance personnel to perform analyses that were not possible several years ago and to be more proactive, rather than reactive, in their pipe management program. In the interim, however, the centralized pipe database is the most inclusive CSCP data source for the Maine DOT. Similar strategies to input all transportation data, including CSCP data, into a data warehouse for use in a larger transportation management system enterprise are being implemented in other states [NCHRP 2002].

FHWA developed a Culvert Management System (CMS) that consists of an online-based software system for repair, maintenance and replacement of culverts. The CMS can assist departments of transportation and other road authorities in proper management of culverts. The software is developed based on inventory of the culverts, condition and rating, work needs (repair or rehabilitation), work funding and prioritization, and scheduling (time of the year and whether in-house or contract). The CMS also includes a flow diagram with accompanying data forms to assist users in successful implementation. This helps in reacting proactively to the situations and also in avoiding breakdowns. The existing functions of culvert management agencies are

automated by CMS, and it allows for inventorying, storage information, current condition of culverts, and developing repair schedules for existing and upcoming locations.

These systems help in developing smart systems that can suggest the frequency of repairs in particular locations and information related to types of pipe to be used in the future. The literature search also revealed that little work has been done on developing a CIMS that is comprehensive. According to Kurt and McNichol, 1991, a complete management information system would involve an evaluation of the life-cycle costs, deterioration models for each culvert type, and effects of different maintenance strategies.

Currently, underground infrastructure assets are accounted for based on a linear depreciation rate and not based on condition assessment of their present state. To ensure long-term durability of CSCP's and required compliance with federal accounting requirements, state 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 "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.
- A comparison of the estimated maintenance cost of infrastructure assets at or above the established condition level is to be made 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.

IIMS's have been developed for pavement and bridges, and some of these systems incorporate maintenance policies (Golabi et al. 1982; Carnahan et al. 1987; Carnahan 1988 and Maze 1998). In many of these systems the condition state of the infrastructure is 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. The deterioration models described above are incremental models since they predict changes over time. Abazai et al. 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 their 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 pipe database has not been utilized to make management decisions. The following section describes the framework needed to develop a CIMS.

Phase I of NJDOT Culvert Information Management System (CIMS)

At present, NJDOT is developing 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 information pertaining to condition assessment obtained during culvert inspection/cleaning, along with representative digital photographs. Associated financial information will also be used in making the required CSCP management decisions. CSCP's in the network should be inspected and condition states should be known to make prudent management decisions.

The NJDOT CIMS is a two-layer (front-end) information management system for the Culvert-Inlet/Outlet Structure Databases.   The 'front' is an Access 2003 application database with user-interfaces and queries for data review and manipulation. And the 'end' consists of several data databases as well as related photo/movie files and report documents.   All the databases are integrated into an effective data management system. Users can review, modify, save and delete database records in CIMS to keep the system data up-to-date and conveniently display them by forms and reports as well as by photos and videos.

The system consists of databases, user interfaces, and a data administration module. It also consists of an inlet/outlet structures module and a culvert segments module.

Databases
The system uses two major data databases: 'CIMS_UploadingDB.mdb' used for CIMS data uploading and 'CIMS_DataSource.mdb' used for CIMS data-manipulation. The uploading-database serves as a template that loads the contractor's databases into the system sequentially.   Based on the uploaded database tables, the CIMS application reorganizes the Inlet/Outlet Structure and Culvert Segment data and saves their assembled records into the data-manipulation database 'CIMS_DataSource.mdb'. This database will be used as the data sources of CIMS user interfaces.

There are also three auxiliary databases: 'All_Records_Pipe_MH_Links.mdb', 'Current_Records_Pipe_MH_Links.mdb', and 'CIMS_DataSource_BK.mdb'.   These databases support data backup operations of the CIMS application and provide linking-relationship information between inlet/outlet structures and their related culvert segments.

<u>**User Interfaces**</u>
The user interfaces consist of a main switchboard form, two data review/edit forms, and several functional sub-forms. These major module forms will carry on the functionality of the system.
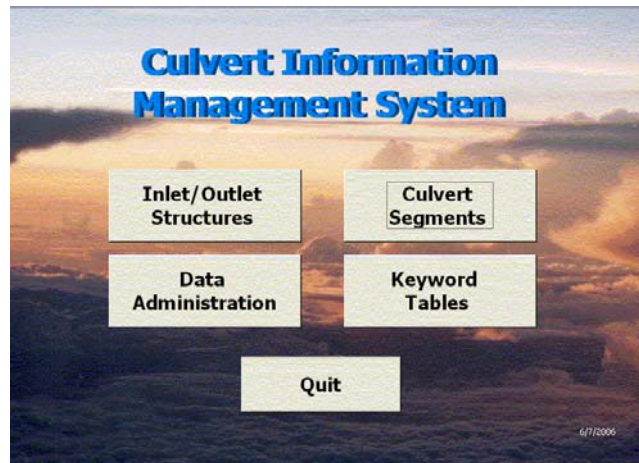

Figure 7: Main Switchboard Form

<u>**Data Administration Module**</u>
Contractors' data are saved on media, such as DVD and tape, in different formats.   It is required to reorganize the data from these media and upload them into our data databases.   In order to facilitate the data uploading processes, a set of appending queries have been created and coded into the Data Administration Module (Figure 8).

Figure 8: Data Administration Module

Clicking the 'Upload New Records' button on the 'Data Administration' form will open a 'Data Processing' window (Figure 9).   There are three groups of functionality for data manipulation:

   (A) Data Uploading – User can upload valid data records from selected source databases into CIMS databases and link related photo files into their records.

(B) Pipe-MH Links – Generates a table that lists Pipe-Manhole relationships for current projects in the CIMS database. This relationship table can be transferred to the Straight Line Diagram program so as to link the 'dots' (inlet/outlet structures) to the 'line' (culvert segment).

(C) Database Exchanges – This will allow users to save current data databases into their backups, or retrieve previously saved data databases as a current data source for review.   Thus, users can save their records by projects or by dates and reduce the CIMS working database sizes.
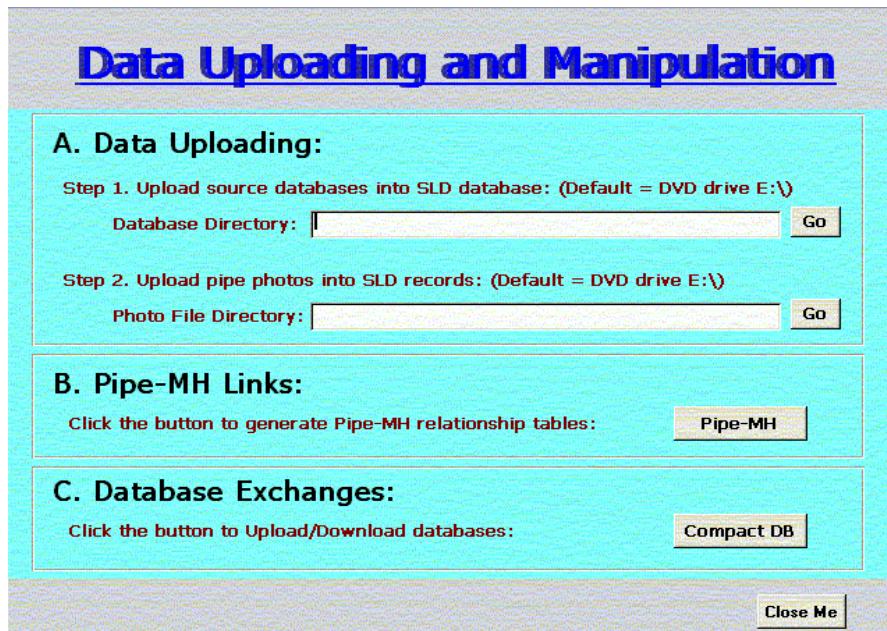

Figure 9: Inspection Data Processing

Inlet/Outlet Structures Module

The Inlet/Outlet Structure form, shown in Figure 10, displays structure IDs and their attributes. To use this form the user first selects a location (Road), then selects a rounded Milepost (one mile per interval) and finally selects the expected inlet/outlet that is close to the round-up milepost value.

Users can also edit any field on this form, fill missing data, and click the 'Update' button to save changes. However, no record deletion will be allowed at the present time. Deletion ability can be added in the future.

Figure 10: Culvert Inlet/Outlet Structure Data Form

Culvert Segments Module

The culvert single record data form, shown in Figure 11, presents pipe segment information. Similar to the Inlet/Outlet structure form, there are three combo boxes on top for the user to narrow down the selection of the particular pipe record. The user has to first select a location (Road, City, State…); then select the start-manhole; and finally select the end-manhole that will refresh the form to present the filtered pipe

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record. The user can also retrieve all records to navigate through by double clicking the location combo box area.

The user also can edit any field on this form; fill-in missing data; and click the 'Update' button to save changes. However, no record deletion will be allowed at the present time. In order to keep data integrity, primary key fields, such as 'Report ID' and 'Video ID' should not be edited. They are supposed to be downloaded from the source database only. Also 'Observations', a sub-form, lists all related observation information, including comments, photo file names, and movie file names. For each observation record, there will be two rows shown on the sub-form so as to allow users to insert two photos for the same record.

Figure 11: Culvert Segment Data Form

This system also allows the user to create a report. Double clicking the 'report' textbox on the culvert segment data form will allow users to save the full path of a related document to the text field. The report itself can be saved at any location on the network. At the bottom of the form, there is a 'Report Preview' button. This will generate a customized report for the current pipe data record. A sample report is shown in Figure 12. On the report, all detailed information about the record will be displayed, as well as, all the observation photos.

Figure 12: Report Preview

The next phase of the project is planned to be a demonstration project to develop the tools needed for a large-scale CIMS, which will include a variety of culvert types. The CIMS demonstration should be a pilot study, and the database created will include selected culvert types and locations that are representative of the storm water drainage system throughout the state. The objectives of the demonstration project would be:

- To predict the remaining service life and the current value of culverts at project and network levels,
- To determine the allocation of NJDOT funds required for culvert cleaning, repair and replacement at project and network levels,
- To determine yearly funds needed to maintain or improve the network level value of all culverts.

CULVERT INSPECTION, CLEANING, REPAIR, AND REPLACEMENT

Meegoda et al. 2004, provides a detailed description of procedures for culvert inspection, cleaning and minor repair, and recommended inspection frequency. CSCP's are divided into three categories based on the following factors: corrosion and erosion, bed load, pH, and culvert size, age and importance. Culverts in the first category are considered fully functional requiring infrequent inspection, while those in the third category require urgent attention. These inspection frequencies will be refined and coupled to the proposed CSCP management policy.

For the past several years NJDOT has performed culvert inspections using analog videos and saved the relevant information on VHS videotapes. These are now being converted to digital videos for permanent storage. Due to their large file sizes, it would be more efficient to process digital videos using a suitable image processing scheme to identify the critical sections and to compare them digitally with historical information to identify the CSCP condition state. The digital image processing required for condition assessment may be carried out during a future phase of this research study. Once the above scheme is developed, the condition states of CSCP's in the network can be obtained by direct inspection or by reviewing stored digital video data. This information is then used to make prudent rehabilitation and replacement decisions.

Relating Conditions States of CSCP for Rehabilitation and Replacement

CSCP's 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 (FHWA, 1995). The deterioration of a newly installed CSCP 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 (Caltrans, 2003). The subsequent loss of parent metal may lead to perforation of the pipe and eventual structural failure. The condition state of

the CSCP identifies the degree of deterioration and distinct changes in structural serviceability. As a CSCP deteriorates its condition state is increased. Meegoda et al. 2004, considered four condition states. A CSCP in Condition State 1 has no visible deterioration or evidence of active corrosion. The time frame a CSCP is in this state largely depends on the effectiveness of factory applied pipe coatings. When surface or freckled rust is observable, the pipe is considered to have moved to Condition State 2. A pipe in this state may exhibit flaking and minor section loss of less than 10% of its thickness. In Condition State 3, a pipe may undergo flaking and swelling with surface pitting that is considered equivalent to a 10 to 30% loss of thickness. When in Condition State 4, the functionality of the pipe is compromised due to extensive deterioration, perforations leading to soil loss, pipe distortion and caving.

The use of appropriate coating materials and thicknesses are key factors in determining the durability of CSCP. 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 (FHWA, 1995). The City of Chesapeake (2004) discusses the metal loss rate due to corrosion and abrasion.

The rehabilitation option that is appropriate for a particular CSCP 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. 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 CSCP's 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.

Rehabilitation/Replacement Options

In this research the level of deterioration of a CSCP was defined based on the condition state, and it is assumed that additional life gained through rehabilitation will upgrade the condition state. CSCP rehabilitation options can be grouped as a) cleaning & painting, b) invert paving, c) pipe-lining, d) in-situ cured liners, and e) in-situ pipe replacement. Table 5 shown on Page 39 illustrates the advantages and limitations of the following rehabilitation/replacement options.

Cleaning and Painting: During the initial stages of deterioration cleaning and painting is viewed as a timely intervention in retarding corrosion. This option is effective for CSCP's in Condition State 2, where corrosion has just begun. Although painting is seen as costly in the short term, it may be found to be beneficial in the long-term. Flaking of

painted metal surfaces is a common problem in galvanized metal surfaces. Flaking takes place due to lack of bond between the applied coats and the surface, and hence would further accelerate corrosion with time. When such regions are encountered, it is recommended to remove all flakes. It is necessary to clean culverts prior to painting to remove rust, dirt and debris. An air-jet could clean small to medium diameter culverts. Industry recommends the use of phosphoric acid solutions to clean the affected areas. The application of a zincplombate primer on cleaned and dried surfaces is recommended prior to applying a durable paint. Cleaned surfaces are to be coated with two coats of single component inorganic zinc or organic zinc-rich paint. The protection provided to the pipe depends largely on environmental factors, and hence local experience may decide on its effectiveness.

Invert Paving: Metal culverts galvanized or coated with asphalt or any other type of protective coating are found unsuitable under high abrasive conditions, and FHWA 1995, recommends invert paving as a viable technique to restore CSCP's. 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 effluent has a pH of 5 or less, protective measures are generally required. Caltrans 2003 discusses invert paving with reinforced concrete as an effective way to rehabilitate corroded and severely deteriorated inverts. A paving thickness of 75-150mm (about 3-6 inches) is recommended based on the abrasiveness of the site. Paving limits typically varying from 90 to 120 degrees for the internal angle. A detailed description of invert paving is given in the FHWA Culvert Repair Practices Manual (FHWA, 1995).

Slip-lining: It involves sliding a new culvert inside an existing distressed culvert and is an alternative to total replacement. This method is much faster than the remove and replace option, and often will yield a significant extension of service life at a lower cost and disruption compared to complete replacement (Caltrans, 2003). The acceptance of the slip-lining process by the industry as a solution to problems associated with corrosion of pipelines has led to an increasing demand for non-structural lining techniques (FHWA, 1995). A wide range of choices is available for culvert slip-lining. These sections can be handled easily compared to longer CSCP sections, and can be connected inside the culvert. Typical slip lining options (Caltrans, 2003, and FHWA, 1995) are plastic pipes, corrugated metal pipes, fiberglass reinforced cement (FRC), and fiberglass reinforced plastic (FRP)

In-situ Cured Liners: In-situ cured liners are made by applying the raw lining material to the appropriately prepared surface of existing pipe and allowing the material to cure. This is achieved by natural or accelerated means. It is usually applicable for larger diameter and shorter sections. The most commonly used in-situ cured liners (Caltrans, 2003; FHWA, 1995 and Persson, 2001) are cement-mortar lining and cured in place (CIP) liners.

In-situ Replacement: In-situ pipe replacement techniques refer to the removal of the existing culvert and installation of the new culvert with little or no new excavation. Typically, the new culvert is being installed while the old culvert is being removed. By

necessity, these liner culverts have smaller diameters than the original culvert, but they typically are more durable and have enhanced hydraulic characteristics. The ability to be used in corrosive environments has also made them more popular. However, as of today, little experience has been documented. At present such systems may require a high initial investment, but the benefits may far outweigh the cost of replacement through excavation. The commonly used in-situ pipe replacement options (Simicevic and Sterling, 2001) are pipe splitting, pipe eating, pipe reaming, and slip lining with polymer pipe.

Table 5: Advantages and Disadvantages of Rehabilitation Techniques

Technique		Advantages	Disadvantages
Cleaning and painting [2]*		Suits less abrasive conditions; paints enriched with zinc act 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 [3]*	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. [3]*	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 [3]*	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 [4]*	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 [4]*		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.

* Condition state

Decision to Repair, Rehabilitate, or Replace

Table 6 lists the rehabilitation options for culverts based on the four condition states as defined on Page 21. It should be noted that CSCP's in Condition State 3 that are not crossing a highway are recommended for replacement with a new culvert. However, a cost comparison with in-situ pipe replacement should be performed. Table 6 also summarizes the recommendations for rehabilitation and replacement of CSCP's that are identified with respect to the four condition states subjected to CSCP size and length. The proposed rehabilitation technique would upgrade the condition state, hence enhancing the service life. For instance, those CSCP's in Condition States 2 and 3 are upgraded to Condition States 1 and 2, respectively.

Table 6: Recommended Rehabilitation Techniques Based on Condition State

Condition State	Description	Culvert Size	Length	Recommended Technique	Improved Condition State
1	No corrosion	All	All	(Do nothing)	-
2	Surface rust or freckled rust with minor section loss	All	All	Cleaning and painting, then schedule another inspection.	1
3	Flaking, swelling with surface pitting, moderate section loss	6 – 12 in.	All	Cleaning and painting	2
		1 – 3 ft.	L<25 ft.	Cleaning, painting and invert paving. Cement-mortar lining Pre-cast concrete lining.	2 2 2

			L>25 ft.	Slip-lining with:
				   PVC liner
				   Fiberglass reinforced cement (FRC) liner
				   Fiberglass reinforced plastic (FRP) liner
					2
					 2
					 2

		> 3 ft.	All	Cleaning, painting and invert paving. Cement-mortar lining Pre-cast concrete lining. Fiberglass reinforced plastic (FRP) liner. Cured-in-place (flexible) liner.	2 2 2 2 2
4	Corrosion advanced with heavy section loss	6 – 12 in.	All	Slip-lining with PVC pipe.	1
		1 – 3 ft.	All	Insert fiberglass reinforced cement (FRC) pipe. Insert fiberglass reinforced plastic mortar (FRP) pipe.	1 1
		> 3 ft.	All	Insert fiberglass reinforced plastic mortar (FRP) pipe.	1

The proposed rehabilitation methods are based on culvert length and size. CSCP's 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 is 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.

Methodologies for Corrective Action
Most of the transportation agencies surveyed do not have a standardized method for pipe repair. The type of repair is dictated by the pipe defect and the experience of the repair personnel (NCHRP, 2002). Very few agencies have CSCP condition records. When a preventative maintenance program is established, these records can be used to determine the rate of deterioration of a pipe, for scheduling of CSCP inspections, and to assist in determining the appropriate time to repair or rehabilitate a deteriorating CSCP.

Comprehensive and regular culvert maintenance activity keeps the structure in a uniformly good and safe condition. Culvert repair activity is carried out when there is a reaction, such as a dip in the roadway caused by a defect in the culvert. According to the National Corrugated Steel Pipe Association, various factors to be taken into consideration to determine whether a culvert requires repairing, rehabilitation, or replacing include:
- Variation from the straight centerline
- Dents or bends in the structure
- Damaged coatings
- Lack of rigidity
- Ragged or diagonal sheared edges
- Uneven laps in riveted or spot welded culvert
- Loose, unevenly lined, or unevenly spaced rivets
- Defective spot welds or continuous welds
- Loosely formed lock seams

Culvert repair activity can be patching, crack sealing, invert paving, lining, or joint work. The type of defect detected in the culvert during inspection activity indicates the problem, as well as in most cases, the type of repair required. Repair work generally does not require a detour, bypass, or lane closure because the activity does not affect traffic flow (Moore et al., 1985).

Culvert rehabilitation is a major undertaking now being addressed by federal, state and local governments. The magnitude of rehabilitation is enormous, but it is often very cost effective when compared to the alternative of new construction.

Culvert rehabilitation can be accomplished by either invert rehabilitation and/or total pipe rehabilitation. When the deterioration is limited to the invert, invert rehabilitation is possible, and is usually done by lining the culvert with concrete. Based on responses from several state DOTs, Alexander, et al., 1994, reported that culverts with concrete lined inverts had been performing satisfactorily. The cost of lining the invert with concrete is found to be around 20-30% of total pipe replacement cost. Lining with concrete is a recently developed method. However, according to one study done by

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Colorado, these kinds of rehabilitated culverts have been used for 13 years and still show no signs of deterioration (LaForce, 1994).

Culverts can be rehabilitated to provide a new, complete service life at a fraction of the cost or inconvenience of replacement. The condition of the rehabilitated culvert can be better than the condition of the original culvert. If the culvert has exceeded the preventative maintenance stage, but it is not at the point where the structural integrity is lost, then rehabilitation is the proper corrective action. However, if the culvert has deteriorated to the stage where the structural integrity, soil support, or the roadway over the culvert, is lost due to excessive deflection, replacement will be the appropriate corrective measure (Ballinger and Drake 1995).

For the case when the culvert is distorted and has lost the strength to continue supporting the applied load, total culvert rehabilitation is carried out, by slip lining. Slip lining is a rehabilitation process wherein a lining is inserted into the deteriorated culvert, and the space between the liner and culvert inside diameter is filled with grout. The resulting diameter is less than the original inside diameter of the culvert. If it is acceptable under those working conditions, the method has several advantages. Small pipes are slip-lined with concrete, concrete lined steel, polyethylene, polyvinyl chloride or thermosetting plastic pipes. Only corrugated steel or aluminum is normally used to slip-line culverts larger than 120 inches in diameter. Slip lining costs from 55 to 80 % of the cost of replacing the pipe.

It was observed that:
- If concrete invert lining lasted for four years or more, its use would be more economical than replacing the pipe.
- Invert lining (concrete) would cost 35% more than the cost of slip lining (aluminum), but the slip-lined pipe would last for 50 years.
- Increasing the thickness of plates forming the invert is an economical strategy for extending service life of pipes.

Culvert replacement is the final option available when the culvert is experiencing advanced deterioration, reduced hydraulic capacity, or increased elevation of the inverts (Alexander et al. 1994). When culvert replacement is done by making an open cut, it is necessary to design a detour, construct a temporary bypass, or stage the construction. Staging the construction allows half of the roadway to be opened to traffic at all times. It also requires that a form of traffic control be put in place. Any form of traffic control at culvert replacement locations is usually expensive; therefore, trenchless methods are preferred.

Replacement can be accomplished by any of the following:
- Realignment
- Hydraulic, structural, and safety improvements
- Change in culvert shape or material

Rehabilitation of culverts requires a complete inspection and evaluation of the existing culvert to determine the best method. Most often, rehabilitation requires merely providing a new wear surface in the invert.

Most state departments of transportation and road authorities do not have guidelines for selecting a culvert rehabilitation method, however, some authorities consider hydraulic capacity, traffic volume, height of fill, expected service life (i.e., based on pH, resistivity, measure of corrosion resistance, and pipe material), and risk assessment in their decision to rehabilitate a culvert.

COST ESTIMATION FOR A PREVENTIVE MAINTENANCE PROGRAM

Having established the condition states of CSCP's in the network, the following financial information is required for CSCP management decisions.
- 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 (μ_i) and variance (σ_i) for each culvert will be used to generate a culvert deterioration curve
- Cost of installation for each culvert, it is also assumed to be the same as cost of replacement ($\$A_{i,t}$)
- 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 ($\$H_{i,t}$)

The above also identifies information that is available from NJDOT and the parameters that will be used in developing the CIMS. Assessing the cost or risk associated with failure is the most challenging issue in effective management of CSCP's. 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 a roadway or across a roadway, and its proximity to critical structures such as subways, hospitals and hazardous waste sites. The NJDOT user cost manual describes the methodology to compute the user cost associated with the traffic delay due to extra travel time and extra travel distance. For a given CSCP, the analysis shown below assumes that $\$H_{i,t}$ is known. It also uses a zero inflation rate and a zero discount rate for demonstration purposes.

Some objectives of the proposed CIMS are: (a) to 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 the ith culvert in the network.

- 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
- Cost of failure ($\$H_{i,t}$) = \$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 the condition state of the culvert during the previous year. Meegoda et al. 2004, predicted the survival probability of a CSCP in urban environments with service time using data from an American Society for Testing and Materials (ASTM) study. It is plotted again in Figure 13, and is identified as CS1 to CS1, 2, and 3, i.e., the variation of survival probability of being in Condition States 1, 2, and 3 having been in Condition State 1 at time t = 0. If the current condition state is known, using the above-mentioned curve, CS2 to CS2, 3 and CS3 to CS3 can be obtained. The curves in Figure 13 were generated from the Markov deterioration model discussed on Page 21 and included in Appendix I. The mathematical derivation for the above will be presented in a theoretical journal appropriate for such analysis; it is used in this manuscript to illustrate the basis for management decisions. However, the authors emphasize 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 CSCP inspection. If the current condition state is unknown due to budgetary constraints the selection is somewhat different, and is also listed below.
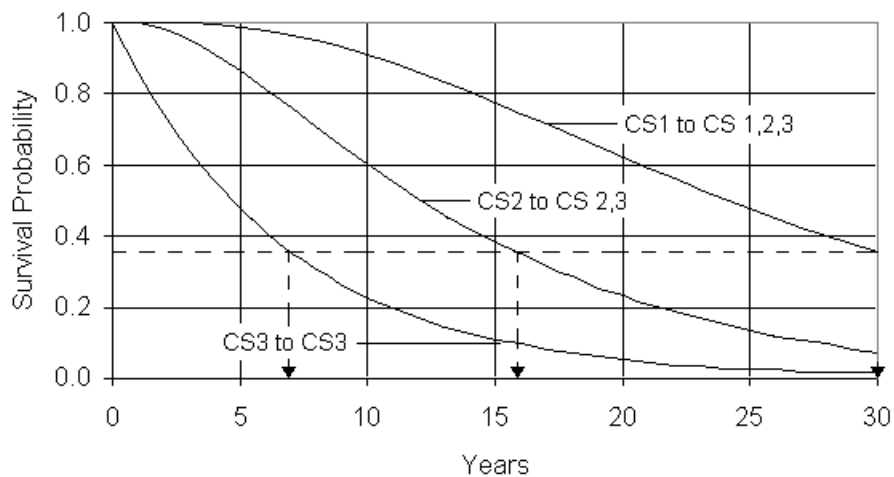

Figure 13: Survival Probabilities of CSCP's in Condition States 1, 2 and 3

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Inspect a Culvert of Unknown Condition State
The proposed inspection frequency for CSCP's in New Jersey is given in Meegoda, 2004. However, the recommendations cited in the referenced report deviate from GASB-34 requirements which should be based on actual condition state. Hence any such deviations should only be made based on analysis. The proposed CIMS could perform such analysis, but it requires the age of the CSCP. The following section illustrates the rationale for decisions embedded in the proposed CIMS.

If the age of a particular CSCP is 10 years, then the survival probability after 10 years is found to be 90% (refer to CS1 curve in Figure 13), and therefore, the failure probability is 10%. Hence the user cost of failure during the current budget period, $\$G_{i,t}$, would be $\$0.1X\ H_{i,t} = (0.1 \times \$500,000 = \$50,000)$. If the decision is to inspect the culvert, then the current cost of inspection, $\$E_{i,t} = (\$30,000)$ has to be compared with cost of failure during the current budget period $\$G_{i,t}$. In this example since $\$30,000 < \$50,000$, the culvert has to be inspected (see Case # 2, Table 7 on Page 46).

Rehabilitate/Replace a Culvert of Known Condition State
The rationale developed in this study considers that a change in condition state occurs when the survival probability for CSCP's in Condition States 1 through 3 reaches 0.35 providing a design service life of 30 years. For a CSCP in Condition State 3, this would give a remaining service life of 7 years (refer to CS3 curve in Figure 13). The current worth of a given CSCP is $\$B_{i,t}$, which is computed based on the remaining service life. Thus for this case, $\$B_{i,t} = \$A_{i,t} \times 7/30 = (500,000 \times 7/30 = \$116,666)$. If the CSCP is to be repaired, the cost of rehabilitation, $\$F_{i,t} = \$200,000$, and $\$B_{i,t}$ have to be compared with the current value of the rehabilitated CSCP. Rehabilitation upgrades the condition state by one state, giving a new remaining service life of 16 years (refer to the CS2 curve in Figure 13). This gives the worth of the CSCP after repair to be $\$C_{i,t} = \$A_{i,t} \times 16/30 = (500,000 \times 16/30 = \$266,666)$. If after rehabilitation (i.e. $\$C_{i,t}$) the CSCP is worth more than $\$B_{i,t} + \$F_{i,t}$, then the decision to rehabilitate is justified. In this example since $\$266,666 < \$116,666 + \$200,000$, the proposed rehabilitation cannot be justified. However, since the CSCP is in Condition State 3 with a high user cost of failure ($\$500,000$), this culvert should be replaced (see Case # 7, Table 7 on Page 46).

Rehabilitate/Replace a Culvert of Unknown Condition State
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 10 year old pipe the survival probability is 90% (refer to CS1 curve in Figure 13) and hence the failure probability is 10%. Therefore, the user cost of failure for the current budget period would be $\$0.1x\ H_{i,t}$ or $\$G_{i,t} = (0.1 \times \$500,000 = \$50,000)$. If the decision is to repair the culvert, then the current cost of rehabilitation, $\$F_{i,t} = (\$200,000)$ has to be compared with the 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 $\$200,000 > \$50,000$ there is no justification for the proposed rehabilitation. One should inspect, obtain condition state, and reanalyze.

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

The state DOT's 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, and thus result in a net improvement in total network asset value. This aspect will be addressed during future research.

The following 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 that are associated with incurred costs. The decisions to be made depend on the state of the CSCP deterioration, and associated costs of inspection $E_{i,t}$, rehabilitation/replacement $F_{i,t}$, or no-action [leaving it to deteriorate] $G_{i,t}$, where t is the year in consideration. Failure costs should take into account the probability of failure of the given culvert, its location, and the consequences of such failures. Estimating $G_{i,t}$ (user cost of failure during the current budget period) is challenging and requires a focused research effort. At this juncture, in order to develop the framework for analysis without the loss of generality, it is assumed that $G_{i,t}$ is known. Hence the objective is expressed mathematically as:

$$\Sigma\ [\ F_{i,t}\ X_{i,t}\ (1-Y_{i,t}) +\ G_{i,t}\ X_{i,t}\ Y_{i,t} +\ E_{i,t}\ (1-X_{i,t})\ ] \tag{3}$$

Subjected to $$Z \geq\ \Sigma\ [\ F_{i,t}\ X_{i,t}\ (1-Y_{i,t}) + G_{i,t}\ X_{i,t}\ Y_{i,t} + E_{i,t}\ (1-X_{i,t})\ \tag{4}$$

Where $X_{i,t}$ and $Y_{i,t}$ are binary variables of value either 0 or 1.

Table 7 provides network level actions for ten culverts for a $1,000,000 budget, and the proposed actions will cost $970,000, which may not maintain the overall condition state of the system. A long-term strategy should be implemented such that improvements either maintain or increase the total network asset value.

Table 7: Culvert Cost and Inspection/Rehabilitation/Replacement Decision

#	Years in Service (T_i)	Condition State	Remaining Service Life	Cost of installation ($A_{i,t}$)	Cost of inspection ($E_{i,t}$)	Cost of rehabilitation ($F_{i,t}$)	Cost of failure ($H_{i,t}$)	Project Level Decision	Network Level Decision
1	5	Not Known	Not Known	500,000	30,000	-	500,000	Do Nothing	Do Nothing
2	10	Not Known	Not Known	500,000	30,000	200,000	500,000	Inspect	Inspect
3	10	I	30	750,000	30,000	200,000	400,000	Do Nothing	Do Nothing
4	Not Known	II	16	500,000	30,000	200,000	300,000	Repair	Repair
5	15	II	16	750,000	30,000	200,000	400,000	Repair	Repair
6	20	Not Known	Not Known	750,000	30,000	200,000	400,000	Inspect to obtain condition state for a decision	Inspect
7	Not Known	III	7	500,000	30,000	200,000	500,000	Replace	Do Nothing

8	24	Not Known	Not Known	650,000	30,000	200,000	500,000	Inspect to obtain condition state for a decision	Inspect
9	Not Known	IV	0	450,000	30,000	175,000	150,000	Replace	Replace
10	28	Not Known	Not Known	450,000	30,000	175,000	150,000	Inspect to obtain condition state for a decision	Inspect

As mentioned before, the framework proposed here represents a preliminary approach to asset management of a network of CSCP's. 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. The findings of these field investigations, and the use of a variety of operations research tools and simulation experiments are necessary for model refinements that will be developed during the next phase of this research.

PROTECTION OF NEW CULVERTS

The protection of new CSCP's can be achieved either by the application of protective coatings or by cathodic protection.

Protective Coatings And Linings For CSCP's

Protective Coatings
Coatings are required to extend highway culvert life. Protective coatings can be barrier coatings or sacrificial metallic coatings or a combination of both.
- *Metallic coatings* are either intended to present a corrosion and abrasion resistant surface to the environment and/or provide protection to the base metal by acting as cathodic protection.
- *Barrier coating*s are used to prevent contact between the material to be protected and the environment.

Field inspections carried out by several states indicated that most coatings are effective in situations where runoff is free of abrasive debris and the water does not contain a high percentage of soluble salts, particularly chlorides. Low pH does not seem to deteriorate the coatings as much as attacking the metal substrate at coating defects (Young, 1980).

The best existing coating systems are asphalt coated and galvanized steel. Increasing the thickness to compensate for expected corrosion and erosion losses is a method of increasing the life expectancy of culverts. However, the degree of expected corrosion and/or erosion must be known for the site involved. Severe corrosion limits the applicability of this method.

Asphalt coated culverts are subject to asphalt de-bonding both in abrasive and non-abrasive conditions. This may be due to water penetration, either through the coatings or through coating defects, alternate freezing and thawing, mechanical abrasion, poor or variable asphalt quality, or inadequate application techniques. Asphalt coatings are effective in controlling culvert deterioration on the exterior surfaces, but are not entirely satisfactory on internal surfaces.

Polymer coatings suffer from poor adhesion in corrosive environments at areas where the coating to metal interface is exposed, such as joints. Some improvements in asphalt performance are possible; these may be in the form of increased adhesion to the galvanized steel and increased abrasion resistance. Some states have stopped the use of asphalt coatings because it was found to provide insufficient service life to justify the cost. Some states reverted to the use of concrete pipe while others are using organic coatings. Concrete is used in severely corrosive areas.

Other coating systems that are used in protecting culverts are urethanes, epoxies, neoprene, fusion-bonded coatings, ceramics, and metalized coatings. These methods are more expensive than the other methods, but they have an advantage in that they can be applied locally only to those areas where needed. Table 8 lists all the available coatings for new CSCP's and their advantages and disadvantages.

Table 8: Comparison of Various Coatings Systems

Coating Type	Advantages	Disadvantages
Asphalt Coated Aluminum	Abrasion does not appear to be a factor.	Poor bond to the Aluminum
Asphalt coated galvanized steel (Conventional method)	Exhibits excellent performance where abrasion and salts are not a factor even in low pH environment.	Subject to deterioration when exposed to sunlight and in a stream where abrasion and erosion take place.
Coal Tar Laminate	Exhibits good performance except under abrasive flows and in low pH and high salt environments	Coal tar is a hazardous material
Polyethylene	Satisfactory performance in acidic flows. Performance under abrasive conditions is not clear.	Exhibits extensive general blistering and de-bonding in areas with high chloride content.
Polyvinyl Chloride	Same as Polyethylene.	Same as Polyethylene
Epoxy Coated Concrete	Epoxy remains intact for over 10 years. No clear improved performance under abrasive conditions.	Subject to slight de-bonding.

Linings For New CSCP's
The following methods used in the rehabilitation of culverts can also be used to increase the service life of new culverts:
- In-place installation of invert paving
- Reline the culvert
- Slip line with slightly smaller diameter pipe or tunnel liner plate
- Inversion lining
- Shotcrete lining
- Cement mortar lining

Relining requires the selection of the relining material, which is dependent on the condition of the culvert and the diameter and/or shape. If the culvert is deteriorated to the point where the structural stability has also been affected, then the choice of material would have to be one having a full cross section possessing sufficient structural capability to withstand the imposed dead and live loads. However, if there is no need to provide for structural support, then only the inverts are repaired.

Slip lining is a trenchless method of rehabilitating an existing culvert with minimum excavation. The availability of polymeric pipes, particularly fusion-jointed polyethylene, opened the door to slip-lining techniques wherein the new pipe string is simply winched into the old pipe. New and rehabilitated sewer and drainage pipes are no longer limited to relatively small diameter fiberglass reinforced plastic (FRP) slip-lining methods. The acceptance of the process by the industry, coupled with the awareness of the problems associated with corrosion of pipelines and culverts, have led to an increasing demand for non-structural lining techniques.

Inversion lining requires the use of needle felt or polyester fiber, which usually serves as the "form" for the liner (Ikerd 1984). This method requires that the culvert be taken out of service during the rehabilitation period. One side of the felt is coated with polyurethane membrane and the other impregnated with the thermosetting resin. The physical properties of the felt and chemicals must be determined for the specific project. Inversion can be utilized on lines from 4 to 108-inch diameter and is applicable for distances less than 200 feet, or where the groundwater, soil condition, and existing structure makes open excavation hazardous or extremely costly. Inversion lining is technically complex when compared with other methods of rehabilitation.

Shotcreting is a commonly used term for substances applied via pressure hoses. Shotcrete is mortar or (usually) concrete conveyed through a hose and pneumatically projected at high velocity onto a surface. Shotcrete undergoes placement and compaction at the same time due to the force with which it is projected from the nozzle. It can be impacted onto any type or shape of surface, including vertical or overhead areas and on to pipes or culverts.

Cathodic Protection

Based on historical performance and measurable results, cathodic protection is the preferred technique for mitigating corrosion. The first application of cathodic protection dates back to 1824 long before the theoretical background was established.
There are two basic types of cathodic protection systems. The simplest is the sacrificial anode system, but the preferred method for corrugated steel culvert pipe is the impressed current system. Impressed current systems require a power supply and a control system. The current flowing must be controlled to give maximum life and avoid damage. The sacrificial anode cathodic protection (CP) system is self-controlling and does not require a power supply.

Although CP systems have been successfully used for the last 25 years to protect corrugated steel culvert pipes, there are still some improvement/development in various aspects of CP, especially in the area of control monitoring and establishment of standards. Cathodic protection is ideally suited for steels suffering from chloride-induced corrosion. Although, it can be used on carbonated induced corrosion and for new structures, there are usually more cost-effective ways of solving problems in these conditions.

A CP system may be monitored either on-site or remotely. On-site monitoring is commonly used for easily accessible structures. For remote structures and a prompt maintenance program, a remote monitoring and controlled system is preferred. Remote monitoring offers significant benefits over manual monitoring including improved quality of data acquisition and reduced operating cost.

This project relates specifically to an impressed current cathodic protection system that will employ a solar powered system to protect the culverts from electrochemical corrosion and deterioration. To ensure a continuous DC power supply, alternative backup battery systems will be used to provide continuous operation during poor sunlight condition. Several companies manufacture remote monitoring units, but a very limited number of companies manufacture solar powered CP units.

A market survey was conducted to identify commercially available solar powered and remote monitoring CP units for the project. The systems available were evaluated against the following criteria:
- The unit must be able to monitor a typical CP system without programming by the user
- For the first phase of the project, the monitoring system may be a simple data logger that will record the output of the CP unit
- The unit must be competitively priced

The units that met the criteria were those from the following manufacturers:
- J. A. Electronics Manufacturing Co. (Solar powered CP and Remote Controlling unit)
- Metretek Inc. (Remote Controlling Units)

- Naps Systems (Solar Powered CP units)

Van Blaricum et al., 1997, developed an eight-step procedure for evaluation of <u>remote monitoring systems</u>. The evaluation focused on factors such as field installation, hardware performance and reliability, software performance, and quality of hardware and software manuals.

The hardware manual supplied by the manufacturer is reviewed and evaluated for clarity, completeness, and conciseness in documenting the preparation and procedures necessary for installing the remote monitoring unit hardware. The manual should clearly explain the tools and equipment required for system installation. Installation sequencing should be ordered, complete, and understandable, and any required post-installation field-testing should be explained (Van Blaricum et al., 1997).

Software manuals are evaluated for their adequacy for both novice and experienced remote monitoring users. It should clearly present the procedures necessary to install the software on the master computer and clearly identify the system requirements. It should show in detail the procedure for using the software, setting the necessary operating parameters, obtaining data, exporting data, exporting data to a spreadsheet, and automated monitoring features.

Installation and configuration procedures may be evaluated based on the software loading time requirements, ease of configuring the software to perform the desired measurements, and the amount of technical support required (Van Blaricum et al., 1997).

Impressed-current Cathodic Protection (ICP) reduces corrosion by minimizing the potential difference between cathode and anode by applying a current through an external source. This enables the structure to be maintained at the same potential by preventing occurrence of the electrochemical reaction. ICP is commonly used to protect underground pipelines, storage tanks, locks, and ship hulls, etc.

Corrosion Cells

A metallic surface exposed to an aqueous electrolyte usually possesses sites for an oxidation (or anodic) chemical reaction that produces electrons in the metal, and a reduction (or cathodic) reaction that consumes the electrons produced by the anodic reaction. These "sites" together make up a "corrosion cell". The anodic reaction is the dissolution of the metal to form either soluble ionic products or an insoluble compound of the metal, usually an oxide. Several cathodic reactions are possible depending on what reducible species are present in the solution. Typical reactions are the reduction of dissolved oxygen gas, or the reduction of the solvent (water) to produce hydrogen gas. Because these anodic and cathodic reactions occur simultaneously on a metal surface, they create an electrochemical cell of the type shown in Figure 14.
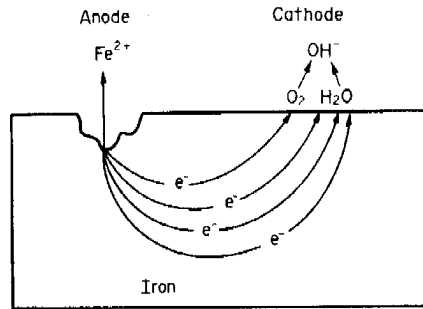
Figure 14: Example of a Corrosion Cell.

The following are four common types of corrosion cells:

1) Dissimilar Electrolyte Corrosion Cells
This type of corrosion occurs when a structure passes through an electrolyte of varying properties. Normally, the electrolyte varies in chemical composition or electrical resistivity. When variations of resistivity occur along the same structure, normally the area of the structure in contact with the lower resistive electrolyte will be the anodic area. The natural electrical potential of a metal in an electrolyte can vary significantly with differences in electrolyte compositions. The development of a potential difference, even between two points on the same structure, can provide the criteria necessary for corrosion to occur.

2) Dissimilar Metal Corrosion Cells
This type of corrosion is more commonly referred to as galvanic corrosion. It occurs when two metals of different compositions are in contact with each other metallically in a common electrolyte. The magnitude of the potential difference between the two metals and the metal with the more negative potential, will determine which metal will be the cathode, which will be the anode, and the rate at which corrosion will occur at the anode.

3) Existing Structure/New Structure Corrosion Cell
This type of corrosion is very similar to dissimilar metal corrosion in that you have an electrical potential between two metals in a common electrolyte. New sections of the same type of metal are commonly used when making repairs or additions to a structure. The unfortunate thing about this type of corrosion is that the newer structure will normally become the anode.

4) Differential Aeration Corrosion Cells
Another important source of corrosion activity on a structure is differential aeration of the electrolyte (commonly soil). In a situation where part of a structure is in soil having a free supply of oxygen (well aerated), and an adjacent area is in oxygen-starved (poorly aerated) soil, the part of the structure in the well-aerated soil will be the cathode, and the part of the structure in the poorly aerated soil will be the anode.

It should be noted that there are many other types of corrosion cells, and the corrosion mechanism is far more involved than stated here. However, the above is provided as basic information and reference for structure owners.

Galvanic Cathodic Protection

A galvanic protection system uses corrosive potentials of different metals. When a more negative metal is connected to a structure to be protected, the metal would sacrificially corrode to protect the structure. The sacrificial anodes are usually made of either magnesium or zinc.

Impressed Current Cathodic Protection

Impressed Current Cathodic Protection (ICCP) systems use the same basic elements as in the galvanic system. ICCP involves impressing a direct current between an inert anode and the structure to be protected. Since electrons flow to the structure (cathode), it is protected from becoming the source of electrons (anode). In ICCP, the anode is buried, and a low voltage DC current is impressed between the anode and the cathode. An ICCP system consists of buried anodes and the pipeline; both are connected to an electrical rectifier, which supplies direct electrical current. Impressed-current anodes, unlike sacrificial anodes, are not required to be naturally anodic to steel. They are mostly made from non-consumable electrode materials that are naturally cathodic to steel. If these electrodes were directly wired to a structure, they would act as cathodes causing accelerated corrosion of the structure they are intended to protect. The direct current source reverses the natural polarity and allows the materials to act like anodes. Instead of corrosion of the anodes, oxidation reactions such as oxygen or chlorine evolution occurs at the anodes, and the anodes are not consumed. Periodic testing is required to ensure proper CP system operation. ICCP relies on an external direct current source such as a rectifier or battery. An anode material is placed in the electrolyte with the structure intended to be protected, and is made more positive than the structure by connecting both the anode and the structure to the direct current supply. Any conductive materials can be utilized as an impressed current anode, but since corrosion takes place at the anode, materials with very low consumption rates are most desirable. Different types of anodic materials are listed below:

- Inert or non-consumable anodes: This type of anode supports other anodic reactions on their surfaces. In environments where water and chloride ions are present, chlorine evolution and oxidation of water is possible.
  - Platinized substrates: Platinum is the ideal permanent impressed current anode material. It is one of the most noble metals, and in practically all environments forms a thin invisible film, which is electrically very conductive.
  - Magnetite: Magnetite is a cheap and naturally occurring material. It is a non-stoichiometric oxide and has an electrical conductivity of $1.25\Omega^{-1}m^{-1}$. Magnetite anodes have been successfully used in the cathodic protection of buried structures and those immersed in seawater.
  - Lida: This is a recently developed anode. It is claimed that it has superior mechanical, consumption and electrochemical properties compared with conventional anodes.

- Semi-consumable anodes: Semi-consumable anodes are such as graphite and high silicon iron. These anodes have been in service since the first industrial electrochemical systems were built.
  - Graphite: Today graphite anodes are widely used. Graphite is now preferred for use in impressed anode materials. It is less porous and has high electric conductivity. But graphite deteriorates more with decreasing pH and increasing sulfate ions concentration. Graphite is not recommended for closed systems. Graphite is generally used in conjunction with carbonaceous back-fills in soil based impressed anode systems.
  - High silicon iron (HSI) alloys: These anodes are also widely used.
  - Lead alloys: The function of lead as an impressed current anode depends on the formation of a protective and electrically conductivity film of lead dioxide, PbO_2.
- Consumable Anodes: This type of anode includes scrap iron or steel and cast iron. The anode is deliberately dissolved to provide the electrons required to polarize the structure. These can be used in buried or under immersed conditions. Due to their high consumption rate the use of such anodes is rather rare unless a redundant source of iron or steel is readily available such as an old ship, a disused pipeline, etc.
- Mixed Metal Oxide Anodes: These tubular anodes are titanium tubes with a mixed metal oxide coating. The mixed metal oxide is a crystalline, electrically conductive coating that activates the titanium and enables it to function as an anode. The mixed metal oxide anode has an extremely low consumption rate. Due to a low consumption rate, the tubular dimensions remain nearly constant during the life of the anode and provide a consistently low resistance anode. Whether operating in soil, freshwater, mud, or seawater, the mixed metal oxide coatings demonstrate very high chemical stability even in environments with very low pH values. The MMO coatings are also not affected by the generation of chlorine. MMO coatings are formed by spraying aqueous salts of the metals on to the titanium substrate and heating the titanium to a temperature of several hundred degrees Celsius.

Preliminary Data Required for Impressed Current Cathodic Protection
- Physical dimensions of a structure to be protected: The physical dimensions of a structure like, length, width, height, etc. are used to calculate the surface area to be protected.
- Drawing of the structure to be protected: The installation drawing should include size, shape, material type and locations of parts of the structure to be protected.
- Electrical isolation: The structure to be protected should be electrically connected to anode.
- Short circuits: All short circuits should be eliminated, i.e., no two systems should touch each other.
- Corrosion history: The corrosion history of the structure to be protected should be surveyed. The corrosion history in the area can be helpful when designing a cathodic protection system.

- Electrolyte resistivity survey: An electrolyte resistivity survey is one of the most important preliminary data. A structure's corrosion rate is proportional to its electrolyte resistivity. If there is no cathodic protection the electrolyte resistivity decreases. Hence, the structure corrodes more rapidly, and vice-versa if electrolyte resistivity increases, the corrosion rate decreases.
- Electrolyte pH survey: Corrosion is also proportional to pH of the electrolyte.
- Electrolyte and structure survey: The potential between the structure and the electrolyte will give an indication about corrosivity. The corrosivity should be at least -0.85 volts. A potential of less than -0.85 volts may be corrosive, and corrosion would increase as the negative value decreases.
- Current requirement: Current density (current required per square foot) is an important part of the design calculations. The average density required for cathodic protection is about 2 milliamperes per square foot.
- Coating resistance: Coating resistance decreases with age and effects structure to electrolyte resistance.

Advantages of ICCP are flexibility, applicable to a variety of applications, current output may be controlled, unconstrained by low driving voltage, and effective in high resistivity soils. Disadvantages of ICCP are increased maintenance, higher operating costs, may interfere with other structures, and needs careful designing. Figure 15 shows an impressed current system.
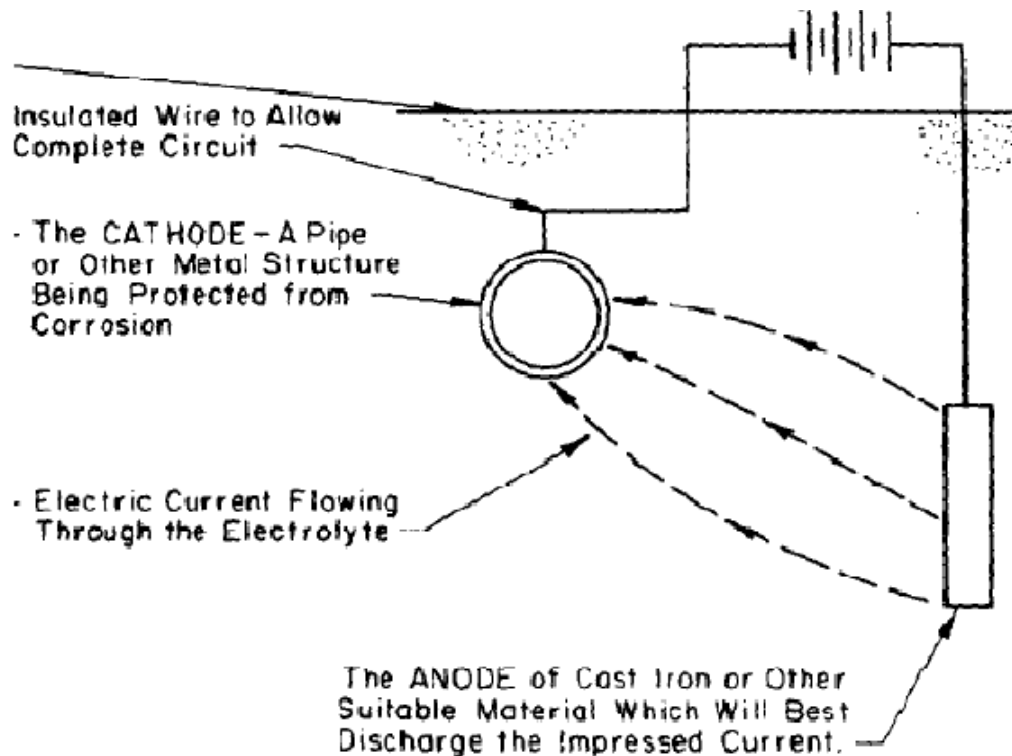

Figure 15: Impressed Current System

Instrumented Cathodic Protection

Instrumented Cathodic Protection (ICP) is a version of ICCP where the variation of the current and voltage is monitored to interpret the corrosion activities. Measurements used to monitor CP systems consist of an open circuit, i.e., one of the poles of the voltmeter is connected in an electrolyte where currents can flow in an open or unrestricted direction. Accordingly, currents resulting from superfluous electrical sources outside of the cathodic protection circuits can affect the corrosion rate and also produce misleading voltage measurements. The basis of this technology is to establish relationships among basic mathematical, chemical and physical equations, and to treat an underground infrastructure as an electrical circuit carrying a multitude of currents that vary in frequency. The technology relies upon an ICP monitoring system that has the ability to filter out all unwanted signals and to isolate the desired signal. This signal has a unique waveform that is based upon the distinguishing characteristics of the underground infrastructure being studied. After the desired signal is isolated, its waveform characteristics can be examined through proprietary analysis techniques. This filtering is similar to the tuner in a television set selecting the frequency of a desired channel. The waveform captured using this filtering technique is mathematically characterized and analyzed. The ICP monitoring system consists of a standard half-cell sensor that is connected to a microprocessor and buried near the pipe for year round readings irrespective of the climatic conditions. Figure 16 shows a schematic of the TransWave monitoring system.
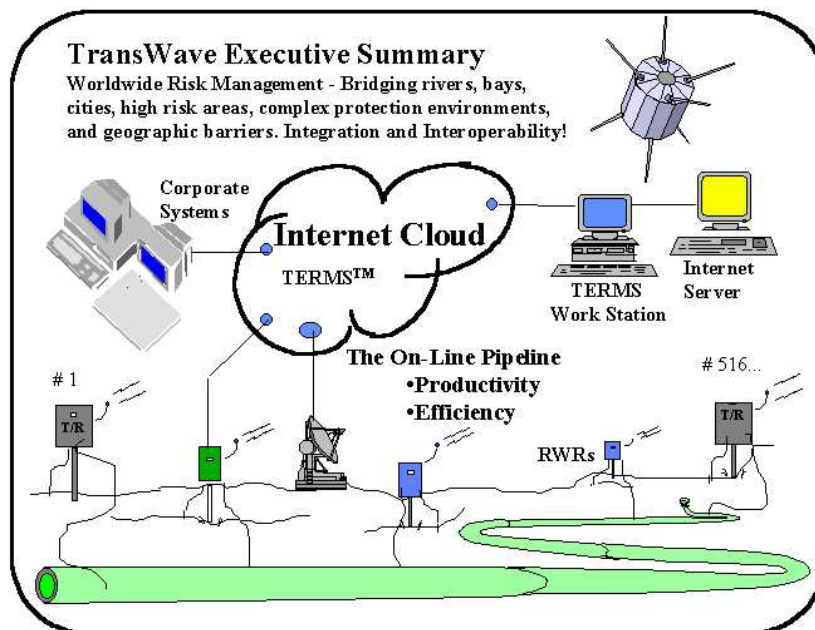

Figure 16: Schematic of TransWave Monitoring System

The stand-alone microprocessors are strategically placed along the pipeline, and in addition to capturing waveform data; each microprocessor has store and forward capabilities for timely and convenient downloading to the host computer. Data can flow from waveform reader boxes to the computer via a variety of communications options including the Internet, wireless communication, and telephone lines. Data collection and analysis are done remotely, in real time, from the desktop.

In addition to CP, "holidays"; i.e., anomalies that are discontinuities or voids in the CP coating, that allow areas of base metal to be exposed to the corrosive environment in contact with the coated surface, are identified. Coating quality can also be evaluated in real time. When corrosion protection anomalies occur, that section of pipe turns red on the computerized map.

Although ICP is a useful technology for coated metallic gas and oil transmission pipelines, where CP systems are commonplace, its application to drinking water and wastewater pipelines is currently limited. However, with the installation of more CP systems to prevent corrosion and protect drinking water and wastewater pipelines, ICP systems for structural health monitoring could be implemented with slight modifications. Additional waveform surveys would also be needed to characterize drinking water and wastewater pipelines and identify sources of external interference.

Experimental Demonstration
A year-long laboratory experiment was conducted at NJIT to evaluate and document the effectiveness of ICP in protecting culverts. Two identical one-foot long sections of 10" diameter CSCP were obtained from NJDOT. The CSCP had been galvanized and coated with asphalt. The asphalt was first removed by heating in an oven, and a 3"x3" section was etched on each to expose the steel metal. The two CSCP sections were immersed in salt water to simulate an extensively corrosive environment. An ALCO Cathodic Protection Rectifier (Model Number: A SAI) that is used in ICP systems was used in this experiment. It is capable of supplying a constant DC current at given voltage, and can be adjusted to maintain a proper output during system's life. One CSCP section was connected to the rectifier, and the other was used as a control. A remote monitoring unit (RMU - Model Number: cRTU-5) from Network Technologies Group, LLC, was also connected to the rectifier. The following section provides the experimental details.

Figure 17 shows the ICP experimental set-up, including the rectifier, and the CSCP section, i.e., the cathode, and the graphite rod that is used as the anode. They are both immersed in the salt water solution. The salt solution was prepared by having 35 gm of salt dissolved in 1 liter of water.

Figure 17: Setup Used at the NJIT Laboratory

Calibration of the RMU: The rectifier is connected to the RMU, which is in turn connected to a computer that records the voltage readings. The RMU was calibrated using the manufacturer's instructions. The voltage was also measured using a multimeter, and the voltages on the RMU were nearly the same as the multimeter. The measured voltages are shown in the Table 9.

Table 9: Measured Voltages by the Multimeter and RMU

Voltage slot (V)	Multimeter Reading (V)	RMU (V)
1	1.63	1.65
2	2.32	2.37
3	3.03	3.05
4	3.81	3.75
5	4.54	4.47

A 1.6 Ω resistor was used for the current measurements. The voltage was measured across the resistor, and the current was calculated accordingly. Table 10 shows the current readings.
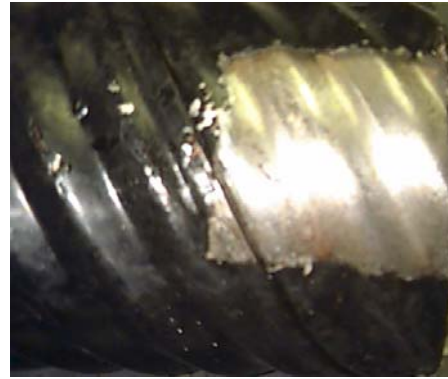
Table 10: Voltage/Current Readings Over the Five Voltage Slots with R = 1.6Ω.

Voltage Slot (V)	Multimeter Reading (V)	Current (A)	RMU (V)	RMU Current (A)
1	1.68	1.03	1.65	1.05
2	2.37	1.48	2.38	1.48
3	3.05	1.93	3.09	1.91
4	3.77	2.38	3.82	2.35
5	4.5	2.84	4.55	2.81

Figures 18a and 18b show the two culverts before being immersed in the salt solution. The individual culvert pipes were immersed in the same salt solution but in separate containers. Figure 19a shows the first culvert connected to the rectifier and immersed in the salt water. The voltage of the rectifier was set to 2 volts. Figure 19b shows the duplicate control system with the second culvert, which was not connected to the rectifier, immersed in its salt solution.

(a) Culvert1- Protected   (b) Culvert2 -Control

Figure 18: Culverts Etched and Prepared for Testing.

(a) Culvert1-Connected to the Rectifier   (b) Culvert2-Control

Figure 19: Test Initiated with the Rectifier (a) and Corrosion Cell Connected (b)

The two culverts were left in the solution for one year, except to be briefly photographed after the first month. At that time Culvert 1, which was connected to the rectifier; i.e., which had ICP, did not rust; while Culvert 2, which was not connected to the rectifier, was slightly rusted. The affected areas of Culvert 1 and Culvert 2 are shown in Figures 20a and Figure 20b, respectively.
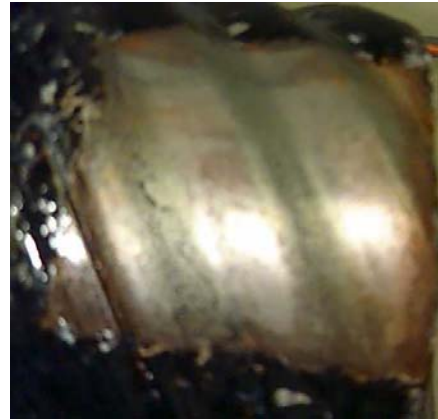
<table>
<tr><td>(a) Culvert1 –ICP Protected</td><td>(b) Culvert2- Control</td></tr>
</table>

Figure 20: Condition of the ICP and Control Culverts after One Month

After one year Culvert 1, which was connected to the rectifier and had ICP, did not rust, but it lost its shining surface, as shown in Figure 21a. While Culvert 2, which was not connected to the rectifier and was not protected, was completely rusted as shown in Figure 21b.
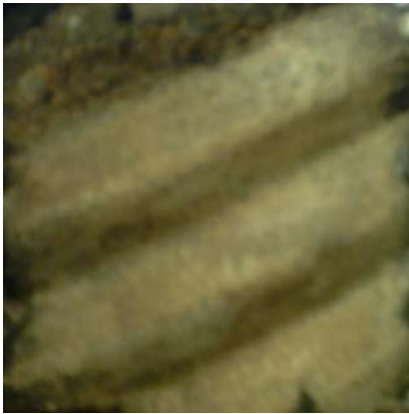
<table>
<tr><td>(a) Culvert 1 –ICP Protected</td><td>(b) Culvert 2- Control</td></tr>
</table>

Figure 21: Condition of the ICP and Control Culverts after One Year

The conducted experiment found ICP; i.e., Instrumented Cathodic Protection, to be a very useful improvement to cathodic protection. ICP is a very effective tool for the protection of steel that is exposed to a highly corrosive environment, such as underground pipes, storage tanks, etc. It is also very cost effective. ICP represents an alternative option for certain metal pipe applications such as metal pipes that are installed with an external corrosion-resistant coating, the proper soil backfill, and with electrically conducting joints.

CONCLUSIONS

Following are the conclusions from this research project.

1. New inspection frequency guidelines for CSCP's in New Jersey were proposed, where the CSCP's are rated at three levels. The rating categories are based on the following factors: corrosion and erosion, bed load, pH, culvert size, age and importance, and they are ranked according to increasing need, e.g., annual inspections recommended for Category III (older pipes with reported problems).

2. A condition state assessment system similar to the Caltrans system, which defines four condition states of culverts, is recommended for use in New Jersey (see Page 21). The condition states should have quantifiable section losses, specific surface features, and a prescribed response associated with each condition state. The four Caltrans condition states are ranked in terms of increased deterioration, and the responses range from "Do nothing" to "Re-lining or replacement".

3. A Markov deterioration model was used to predict the future condition state of new CSCP in urban and rural settings. The transition probabilities were based upon inspection data and corrosion studies. The model was extended to predict the future condition of new CSCP in both settings over a 30-year life. It should be noted that the Markov model does not take into account the effects of maintenance or rehabilitation. In the next phase of this research project a Weibull distribution was used to predict the remaining service life of CSCP and other culverts. The Weibull distribution provided better agreement with pipe corrosion data that became available subsequent to the completion of this project.

4. The guidelines, system, and models in Conclusions 1, 2 & 3, provide a basis for developing a comprehensive plan for inspection, cleaning, condition assessment, and prediction of remaining service of CSCP.

5. 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.

6. NJDOT is currently developing a Transportation Asset Management System (TAMS) based on its Straight Line Diagrams. The proposed CIMS may be a subsystem of TAMS. At present TAMS is collecting culvert information including inspection and condition assessment data and representative digital photos. Digital video files will be stored separately.

7. In this research, CSCP deterioration is defined based on condition state and the assumption that life added through rehabilitation results in an upgrade of the condition state. Rehabilitation options can be grouped as (a) cleaning/painting, (b) invert paving, (c) slip-lining, (d) in-situ cured liners, and (e) pipe replacement.

8. Proposed rehabilitation methods are based on culvert length and diameter. CSCP's with small to medium size diameters (i.e., 6-12 inches and 1-3 feet diameters) 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).

9. The proposed CIMS is based on the condition state of the culvert during the previous year and the predicted variation of survival probability of a CSCP with service time data developed from an ASTM study. Plots showing the variation of survival probability when in Condition States 1, 2 and 3, having initially been in Condition State 1, were used to illustrate the basis for management decisions. For actual implementation of CIMS such curves should be generated from historical data or from laboratory tests that mimic field conditions. If the current condition state is unknown, a probabilistically predicted value may be utilized.

10. The proposed CIMS model will optimize the allocation of annual maintenance budgets by determining the culverts needing inspection and rehabilitation/replacement. The model will also estimate the minimum yearly budget requirements for a given planning horizon so that the aggregate condition state; i.e., the total network asset value, is maintained or improved, satisfying GASB-34 requirements. In addition, the CIMS can be used to make project level decisions to inspect, rehabilitate/replace, or do nothing.

11. 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. At network scale, the allocation of funds is determined based upon an initial budget, and the optimum sequential path in the annual decision making process may be determined using a combination of operations research tools.

12. CIMS goals can be based on the least annual cost, best long-term savings over various time spans, or lowest risk based, etc. However, the primary objectives are: (a) the overall system value or condition should be determined for a given time period, e.g., 10 years, (b) the process should have realistic goals, and (c) the criteria for success should be clearly defined.

13. The first phase of the CIMS was implemented to store culvert inspection data.

14. An automated methodology is proposed to bridge the gap between image analyses used to identify internal defects in pipelines and culverts, and the subsequent condition state assessment analysis.

15. The literature survey revealed that no such fully automated system exists in theory or practice. The study presented in this research can be used as a starting point to formulate better methodologies, which then can be directly put into practice in the field.

16. The image analysis methodology was tested only on a select group of images, using a C-language program developed at NJIT. The methodology relies heavily on learning from previous experience, especially when deciding, (1) how to skip consecutive frames, (2) how to relate pixel area information to physical surface area information, (3) how to correlate pixel gray-values to actual observed depth of defects, and (4) how to choose correct perspective scaling and lighting correction factors.

17. Further work is needed to formulate a set of image analysis rules, which would lend themselves to easy automation and take care of the above issues. The

rule-based condition state rating scheme is attractive because multi-valued logic, such as fuzzy logic, can be used to quantify linguistic terms (such as *small*, *large*, *very deep*, *not too shallow,* etc). This will also follow from a well-documented learning stage, where image data and actual observed data are correlated.

18. The results of laboratory experiments performed to evaluate the effectiveness of ICP showed that ICP can significantly reduce corrosion even in severely corrosive environments.

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APPENDIX I- The Markov Deterioration Model

In order to predict the remaining service life of CSCP one needs the corrosion rate and the pipe age. There is very little measured data on corrosion of CSCP. An extensive search for data revealed that the corrosion rate increases with the age if the surface is free of rust. However, the rust build-up decreases the corrosion rate. Hence it was concluded that it is reasonable to assume a uniform corrosion rate for CSCP with the age. The best usable data for remaining service life prediction comes from an American Society for Testing and Materials (ASTM) study of corrosion of carbon steel from 1960 to 1964 at 46 locations, including 14 locations in other countries. The specification of the carbon steel specimen used for this study is comparable to that defined by ASTM A242. The locations ranged from tropical to polar, industrial to rural, and marine to arid. Based on the above data, 3.0 milli-inch/year (.003 inch/year) recorded at Bayonne, NJ (Boyer and Gall, 1985) was selected as the worst case and 1.5 mil/year recorded at a rural environment (Boyer and Gall, 1985) was selected as the mildest corrosion rate for our research.

Inspection data can be used in estimating the transition probabilities for the chain process, but there are very little historical data. Hence the transitional probabilities for each condition state are computed using the half-life of CSCP and the number of years it takes to deteriorate to that state. Hence the following was computed:

Condition State 1: Assuming an average corrosion rate of 3 milli-inch/year and gauge 18 (.052"), the number of years to reduce the section by 50% is approximately 8.7 years. Hence, the transition probability P(1,1) that the system will remain in this state (Condition State 1) after one year is computed from the following equation.

$$P(1,1) = (50\%)^{1/8.7} \qquad\qquad (5)$$

Hence, P(1,1) is 92.3%. Therefore, the probability that CSCP will deteriorate to Condition State 2 after one year, P(1,2), is 7.7% (100.0% - 92.3%) since the sum of the two probabilities is 100%. Since Condition States 3 and 4 cannot be reached from Condition State 1 after one year, P(1,3) = P(1,4) = 0.

Condition State 2: This is computed relative to P(1,1) in a similar way as above. Condition State 2 occurs when the section loss is 10%. Assuming an average corrosion rate of 3 milli-inch/year and gauge 18 (.052"), the number of years to reduce the section by 10% is approximately 1.7 years. Hence, assuming a similar distribution, the transition probability P(2,2) that the system will remain in this state (Condition State 2) after one year is computed from the following equation.

$$P(2,2) = (0.9)^{1/1.7} \times P(1,1)/100\% \qquad\qquad (6)$$

Hence P(2,2) is 86.7%. Therefore, the probability that CSCP will deteriorate to Condition State 3, P(2,3) is 13.3% (100.0% - 86.7%) since sum of the two probabilities is 100%. Since Condition State 4 cannot be reached from Condition State 2 after one

year, hence P(2,4) = 0. Also, since there is no cleaning or rehabilitation, Condition State 2 cannot move to Condition State 1 after one year, hence P(2,1) = 0.

Condition State 3: This is also computed in a similar way as above. Condition State 3 occurs when the section loss is 30%. Assuming an average corrosion rate of 3 milli-inch/year and gauge 18 (.052"), the number of years to reduce the section by 30% is approximately 5.2 years. Hence, assuming a similar distribution the transition probability P(3,3) that the system will remain in this state (Condition State 3) after one year is computed from the following equation.

$$P(3,3) = (0.7)^{1/5.2} \times P(2,2)/ (0.9)^{1/1.7} \qquad (7)$$

Hence P(3,3) is 86.2%. Therefore, the probability that CSCP will deteriorate to Condition State 4 P(3,4) is 13.8% (100.0% - 86.2%) since sum of the two probabilities is 100%. Since there is no cleaning or rehabilitation, Condition State 3 cannot move to Condition States 1 or 2 after one year, hence P(3,1) = P(3,2) = 0.

Condition State 4: This condition is the failure state, hence P(4,4) is 100%. This is known as the absorbing state from the Markov chain theory. Since there is no cleaning or rehabilitation, Condition State 4 cannot move to Condition States 1, 2 or 3 after one year, hence P(4,1) = P(4,2) = P(4,3) =0.

The results of the above computations are summarized in Table I-1.

Table I-1: Condition States for CSCP's.

From Condition State	To Condition State			
	1(New)	2	3	4 (Failure)
1 (New Culvert)	92.3	7.7	0.0	0.0
2	0.0	86.7	13.3	0.0
3	0.0	0.0	86.2	13.8
4 (Failure)	0.0	0.0	0.0	100.0

Based on the above transition probabilities, the predicted CSCP condition states are reported for a 30-year period in Table I-2. Similarly, the results for rural environments with a corrosion rate of 1.5 milli-inch/year with the associated transition probabilities are also shown in Table I-2. The analysis assumes that no maintenance or corrective actions (e.g., cleaning, repainting, rehabilitation, or replacement) has occurred during this period. The sum of the values in each column equals 100%, since the culvert must be in a particular condition at any point in the future. Based upon this analysis, the future performance of new CSCP's for both environments is shown in Figure I-1. The probability of survival of CSCP's with time shows that CSCP in an urban area has a 65% probability of failure after 30 years, if no corrective or maintenance action is performed, while a CSCP in a rural environment has a 24.5% probability of failure. The current model does not include the effects of maintenance or corrective actions that alter the condition state.

Table I-2: Prediction of future condition state of a culvert in urban and rural environments

| ENVIRONMENT	STATE	YEAR	0	2	4	6	8	10	12	14	16	18	20	22	24	26	30
URBAN	1 (New)		100	85.2	72.6	61.8	52.7	44.9	38.2	32.6	27.7	23.6	20.1	17.2	14.6	12.5	9.0
	2			13.8	22.1	26.6	28.5	28.7	27.8	26.1	24.1	22.0	19.8	17.6	15.6	13.8	10.5
	3			1.0	4.8	9.4	13.7	17.3	19.8	21.5	22.3	22.3	21.9	20.9	19.8	18.4	15.4
	4 (Failure)				0.5	2.2	5.1	9.2	14.2	19.8	25.8	32.1	38.2	44.3	50.0	55.4	65.0
	STATE	YEAR	0	2	4	6	8	10	12	14	16	18	20	22	24	26	30
RURAL	1 (New)		100	92.2	84.9	78.3	72.1	66.5	61.3	56.5	52.0	48.0	44.2	40.7	37.5	34.6	29.4
	2			7.6	13.5	18.2	21.7	24.3	26.2	27.4	28.0	28.3	28.2	27.9	27.3	26.5	24.7
	3			0.3	1.4	3.2	5.3	7.5	9.7	11.8	13.8	15.6	17.1	18.4	19.5	20.4	21.4
	4 (Failure)				0.1	0.3	0.9	1.7	2.9	4.3	6.1	8.2	10.5	13.0	15.7	18.5	24.5
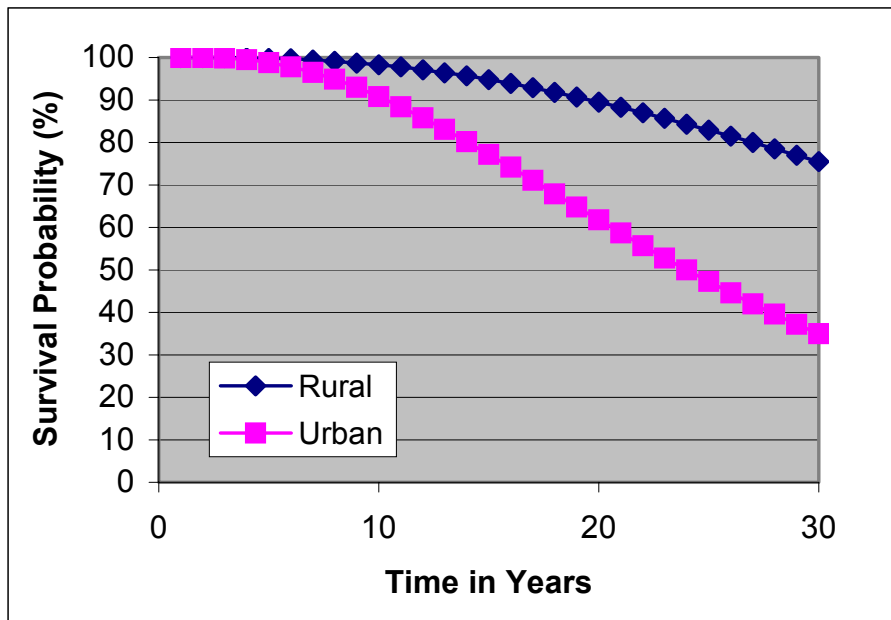
Figure I-1: The survival probability of CSCP's with time in different environments

Prediction of Remaining Service Life

If the current condition is known, the Markov deterioration model can predict the remaining service life of a CSCP. If the condition state of CSCP in year n is x, then the probability distribution of a CSCP reaching Condition State y in year n+1 (or in an additional year) is given by the following equation (Hoel et al., 1972).

$$P_x(T_y = n+1) = \sum_{z \neq y} \left\{ P(x,z)P_z(T_y = n) \right\} \tag{8}$$

Please note that z can take on all the values except y. If y is assumed as the failure state, and there are four condition states, then z=1, 2 or 3. T is the time in years and P(x,z) values are those computed before.

Assuming a current condition state, Equation 8 can be iteratively used to find the number of years for a given probability of a CSCP failure. A computer program was developed at NJIT for this purpose. It requires the corrosion rate, culvert thickness, expected probability and current condition state as input. From this program the number of years for 90% probability of a CSCP failure in an urban environment from Condition States 1, 2 and 3 was found to be 45, 27 and 15 years, respectively. Similarly for a rural environment, the results were found to be 95, 54 and 30 years respectively.

During the second phase of this project it is proposed to expand the above model to include the impact of cleaning and rehabilitation on service life. Cleaning or rehabilitation of CSCP's will affect their performance and influence their probability of survival. Quantifying these effects and incorporating them as improvements to the model is critical to long-term planning and asset management.