University of Alberta

A Comparative Analysis on Sewer Structural Condition Grading Systems Using Four Sewer Condition Assessment Protocols

by

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Abstract

Pipeline condition assessment is a primary task in running an efficient urban asset management program because in the case of system failure, the consequences can be significant to both municipalities and users. Selecting a suitable assessment protocol is crucial for municipalities, since the rehabilitation plans and network prioritization are set based on the structural rating system introduced by the selected protocol. Currently, North American municipalities use different condition assessment protocols, some of which are internationally-accepted, while others are developed based on local needs. This thesis compares structural condition grading systems using four condition assessment protocols; National Association of Sewer Service Companies' Pipeline Assessment Certification Program, the Fourth Edition of Water Research Centre's Sewerage Rating Manual, and early and modified editions of the City of Edmonton's condition assessment standard. The differences and similarities among the four protocols are identified by performing surveys on more than 20,000 of sample pipelines. As a result, accuracy of each protocol is also established and presented.

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Glossary

CCTV	Closed Circuit Television
COE	City of Edmonton
NAAPI	National American Association of Pipeline Inspectors
NASSCO	National Association of Sewer Service Companies
PACP	Pipeline Assessment Certification Program
RDBMS	Relational Database Management System
SR	Structural Rating
SRM	Sewerage Rehabilitation Manual
SSET	Sewer Scanners and Evaluation Technology
WRc	Water Research Centre

Chapter 1: Introduction

1.1 Background

In Canada, similar to many other countries municipalities are in charge of constructing and managing most of the urban infrastructure. A limited municipal budget, funded directly by the tax payers, must be split between new construction and rehabilitation of the existing aged and deteriorated infrastructure (Mirza, 2007). Maintaining the existing infrastructure can be a more challenging task in comparison to the new construction projects for the municipalities, due to involvement of established service facilities in the citizens' everyday life on a continuous basis. Due to such restraints, maintenance and rehabilitation of deteriorated infrastructure requires having an effective asset management plan in place.

Waste water system, being a major contributor to the backlog of aged infrastructure has a high level of importance for the following reasons:

- Since the system is buried under the ground, the deterioration rate is difficult to control. Also, in the case of system failure, replacement is very expensive, aside from the costs associated with possible disturbance to the existing network.
- Serious environmental and health concerns associated with waste water systems.

With regards to these reasons waste water asset management has been in the center of municipalities' attention in the past two decades (Mirza, 2007). The main objective of an effective asset management system is to maintain the asset within an accepted level of quality at lowest costs.

An effective asset management system, takes the followings into consideration (Opina, 2010):

- Inspection of asset, and assessing its condition,
- Accurate analysis of failure chances,
- Studying the consequences of asset failure,
- Financial restrictions associated with the mentioned tasks.

Assessing pipeline conditions is a primary task in running an efficient asset management program because in the case of system failure, the consequences might be significant in terms of costs, and, health and environmental issues for municipalities and users. This task functions based on a condition assessment protocol, which is a key element within the asset management program. The protocol defines a defect coding system that is used to grade the pipeline’s current conditions by deducting value points from the pipe segment for different types of defects inspected in the pipeline (NRC, 2004).

Sewer condition assessment protocols assess sewer pipelines for two particulars; Structural stability and operation and maintenance serviceability.

Operation and maintenance serviceability assessment considers how effectively a segment of pipeline contributes to the network capacity. While service defects, such as debris, roots, encrustation, infiltration, and protruding services affect the serviceability of the pipeline, they are no threat to the structural integrity of the sewer pipelines. Asset management programs develop maintenance plans based on condition assessment results. Under such plans with proper prioritizations, service defects could be repaired with no need for major rehabilitation or replacement of the pipe.

Structural assessment, on the other hand, looks for those types of defects which are directly related to the sewer pipe physical characteristics and their existing conditions. Defects such as cracks, fractures, deformations, joint displacements, open joints, and surface damages fall under this category. These defects require eventual repair to prevent the pipe from further deterioration.

Replacing underground sewer pipes is one of the most expensive tasks in any asset management program (Beck, 2008). Besides the heavy costs associated with open excavation operations, the aftereffects such as traffic bans and service interruptions are major challenges for municipalities. Therefore, a proper recognition and assessment of pipelines' structural defects plays a key role in avoiding extra rehabilitation costs. Since most of the rehabilitation projects are meant to repair structural deficiencies in the pipelines, the outcome of the protocol's structural condition assessment is the most decisive tool for the aforementioned decision making process.

There is currently no Canadian national standard for pipeline condition classification/assessment. Therefore different cities in Canada use different protocols. For condition assessment and life expectancy of assets, some large Canadian municipalities use Water Research Centre (WRc)'s Sewerage Rating Manual (SRM). Some others use Pipeline Assessment Certification Program (PACP) developed by the National Association for Sewer Service Companies

(NASSCO). Also, a Canadian training manual on sewer condition classification was developed by the North American Association of Pipeline Inspectors (NAAPI), based on the WRc's protocol (Allouche and Freure, 2002).

Some of the large Canadian cities have developed their own sewer condition classification manual. The City of Edmonton developed its own sewer condition assessment protocol based on the second edition of the WRc's protocol in 1996. This protocol is the foundation of the asset management program developed by the city, is still officially in practice by the City of Edmonton. In 2010 a revised edition of the standard's structural condition assessment section was published by the City of Edmonton, entitled "Sewer Pipe Structural Condition Rating System Assessment Final Engineering Report". The protocol has a new approach to structural coding and rating system. This edition of the standard has not been implemented by the City of Edmonton yet. Therefore, both of the early and modified editions of the City of Edmonton's protocol are being considered in this thesis.

The sewer condition assessment protocol plays an important role in the execution and success of the municipalities' sewer infrastructure management programs. If the results of the inspection stage do not reflect the actual physical condition of the pipe, maintenance and rehabilitation plans would lack reliability simply because they would aim at not properly selected targets. Such unreliability will cause waste of money and time, as well as possible aftereffects that might come about as the consequences of such plans.

Normally, protocols assess the condition of the pipelines in two steps. The first step includes recoding the defects which are detected in the inspection process. Each protocol has its own system for categorizing and coding different defects and features observed during the survey. There are usually four categories of codes:

- Structural: For recording the physical deficiencies of the pipe's structure, such as cracks and fractures.
- Operational and maintenance: For recording pipe deficiencies which are caused by insufficient maintenance, such as encrustations.
- Construction: For recording different features which are observed during the survey. Service laterals are instances of this category.
- Miscellaneous: For keeping track of the information related to the survey itself, such as the start and finish points.

Inspection quality, defect recognition ability, and knowledge of the adopted protocol are the most critical factors in this step, meaning that the inspection and coding phase directly rely on the operator's experience and judgment.

The second step uses the results from the first step to build the municipal sewer system condition database, and structural rating of the network segments as well as service and maintenance rating. Each protocol has its own criteria to define a numeric scale, in which each number in the scale is assigned to a certain defect. In this process, usually defects are considered in an individual order, and their association with other nearby defects or the location of occurrence does not change the number which is assigned to the defect. Having assigned all the numbers to the defects detected throughout one pipe segment, protocols have certain numerical procedure to calculate the overall rating of the pipe segment.

The NASSCO PACP, WRc SRM4, and both editions of the City of Edmonton condition assessment protocols which are studied in this research use a one to five scale for showing different physical states of a pipeline segment. Each of the numbers in the scale represents a condition. One and two stand for excellent and good conditions respectively. Three represents fair and four means the segment is in poor conditions. Lastly, if a pipe segment receives a score of five, it requires urgent attention.

Since all of these standards use the measurement scales established by the WRc, the interpretation of these grades and subjective terms are almost universal and common.

The pipelines' structural defects affect major rehabilitation or replacement plans. The costs of these sorts of plans and actions are significantly higher compared to maintenance plans (Mirza, 2007), as well as severe destructive aftereffects in case of structural failure of the pipes (NRC, 2004). Hence, this study mainly focuses on structural coding and rating systems of the aforementioned four sewer condition assessment protocols.

From a structural point of view, there are certain elements which should be taken into account in each of the assessment phases for selection of the most effective standard and ultimately implementation of the rehabilitative plans at reasonable costs. In the inspection and coding phase, the coding system should cover a wide range of defects and meanwhile, should be straightforward. This means that under similar circumstances which the operators receive the same training and have the same level of expertise, their interpretations of the codes should not differ from each other. Otherwise, the standard is not capable of addressing the actual structural condition of the inspected pipeline. If the codes are vague and not easy to distinguish, or too similar to each other that they might be mistaken with one another, even experienced operators may have very different approaches in coding the pipelines' defects. This results in the assessment phase to be based on the inspection results which do not properly represent the physical condition of the pipe segment.

The second phase, which is the structural rating phase, should not be underrated in importance, since most of the major rehabilitative and prioritization decisions are planned based on the results of this stage of the assessment (Water Environment Foundation, 2009). If the assessment results are not compliant with the actual structural situation of the pipe segment, there will be a huge inconsistency in the later prioritization of different network zones for rehabilitative actions, which are planned directly based on the results of this phase. For instance, if the pipe segment is recognized to be at the middle stage of its useful life but the assessment results indicate that the pipe segment is at grade five, meaning that it requires immediate attention, the segment will receive a higher priority for rehabilitation. This inconsistency will have its long-term effect on any rehabilitation plan and of course, its budget distribution.

These results are also used to develop the municipal network deterioration curves that are used to establish the useful life of pipes based on their material, and the sewer system type which they are serving.

1.2 Problem Statement

The validity of the currently available condition assessment protocols has barely been evaluated. They were compared only occasionally to each other. Almost no published articles are available in the literature on factors and guidelines that help municipalities select the most effective condition assessment manual for their asset management programs. NRC (2004) conducted a comparison on different condition assessment protocols which are adopted and implemented by Canadian municipalities. Condition grading methods of the protocols are described and the deduction scores for each category of defects are reviewed in the article. However, the criteria used by the pipeline assessment protocols to establish the conditions of sewer pipe segments have not been examined. The causes of the existing differences in the results of pipeline condition assessments performed by different protocols have not been examined in the state of the art either. Since the budget which is assigned to rehabilitation projects by the municipalities is limited (Mirza, 2007) and the allocation of resources is in direct relativeness to the condition assessment results, the selected protocol's assessment outcomes ought to result in time and cost saving of the rehabilitation and replacement plans and operations.

1.3 Research Objectives

The primary objective of this study is to compare the structural condition assessment and grading approaches, developed and used by the NASSCO's PACP, the fourth edition of the WRc's SRM, and the City of Edmonton's early and modified editions of sewer condition assessment protocol. Such a comparison illustrates the accuracy of each of the studied protocols in describing and assessing the structural condition of the sewer pipe segments relative to the actual conditions of the surveyed pipe segments. The main objective can be achieved through the following sub-objectives:

- Comparing qualitatively the structural coding systems of the mentioned protocols, by using the codes' descriptive features.
- Comparing the protocols' structural rating systems, by studying their decisive factors on structural condition rating outcomes for selected sewer pipe segments.
- Identifying the advantages and disadvantages of each of the protocols under study in terms of accurate representation of the actual structural conditions of pipes, cost and time effectiveness, and ease of implementation.

1.4 Research Overview and Methodology

This study mainly focuses on comparing the NASSCO's PACP, WRc's SRM fourth edition, and both early and modified editions of the City of Edmonton's Sewer Pipe Condition Classification Manual. The comparison is made on the approaches used in condition assessment protocols for structural defect inspection and rating systems.

A detailed qualitative comparison between the structural defect coding systems used by each protocol is conducted. Using the descriptions of the defects provided in the protocols, the codes common among all four coding systems are mapped out. The defect codes in one protocol with no equivalent in the other protocols are also introduced.

As part of the practical comparison between the standards, 20 segments of sewer pipelines with different diameters, materials, and sewer system types are selected from different neighbourhoods of Edmonton. The structural defects in the pipelines are coded based on the early and modified editions of the City of Edmonton's protocol, the NASSCO's PACP, and the fourth edition of the WRc's SRM. The selected segments are then structurally graded under each standard's condition grading criteria. The results of this real-world experiment are taken into consideration for a broader deliberation.

In order to compensate for the limited number of in-service pipelines included in the study, a complete database of the aged sewer pipes' CCTV inspections from Edmonton is next used in a similar experiment. In doing so, all of the four aforementioned standards are implemented to structurally code and grade the pipeline segments in the database. For this purpose, a computer tool is developed to convert different protocols' coding systems to each other. The tool is developed in structured query language (SQL) within the relational database management system (RDBMS) which is designed to maintain the database records. Using the variety of features which SQL provides, the tool is capable of structural grading of the pipeline segments, as well as comparing the grading results for the each of the pipe segments.

The findings from reviewing and assessing the 20 segments are then examined for compliance with the results of analyzing the CCTV database. The protocols grading results are then compared pairwise and the observations are discussed. The factors causing diverging assessment results from different protocols for the same pipe segments are pointed out. Also, each protocol's coding and grading system's inefficiencies and inconsistencies in structural rating are discussed.

The findings about each protocol's inconsistencies are validated by designing artificial pipe segment case scenarios using such inconsistencies. The reason for designing these scenarios is to compare the protocols' assessment results with the pipe segment's actual physical condition in each scenario. Industry experts are asked to comment on the physical conditions that the pipe segment of each scenario is at. By comparing the protocols' assessment results with expert opinions on the scenarios, the protocol with the closest results to actuality is introduced.

1.5 Description of the Chapters

The results of this research are presented in the following chapters:

- Chapter 1: Introduction –provides a background on the area of research for the study, as well as problem statement and research methodology.

- Chapter 2: Literature Review – includes a discussion about the importance of sewer condition assessment protocols for municipal asset management programs. The four protocols which are used in the study are also described in this chapter.
- Chapter 3: Qualitative Comparison of Structural Defect Coding and Condition Grading Systems – includes a comprehensive qualitative comparison between the protocols' coding systems, where the equivalent for one protocol's defect code is mapped out in the each of the other three protocols and those with no equivalents are introduced as well. The structural condition grading approaches adopted by the protocols are also compared and observations are discussed.
- Chapter 4: Quantitative Comparison of the Four Structural Condition Assessment Protocols Using 20 Pipe Segment Surveys – twenty CCTV surveys for different sewer types are reviewed, structurally coded, and graded by all of the four protocols. The results are compared and the observed facts are presented and discussed.
- Chapter 5: Implementation of the Four Protocols in a Sewer CCTV Database Using Structured Query Language – introduces a full CCTV database of 15 years of pipeline inspections. The records are coded and graded by the four standards using structured query language within the relational database management system which is developed for better analysis of the records. The protocols' assessment results are then compared pairwise and observations are discussed.

- Chapter 6: Validation of the Findings by Comparing the Protocols' Results with Expert's Opinions – the observations from the previous chapters are implemented in seven artificial scenario cases which are structurally examined by each of the protocols. The assessment results by each protocol are compared with comments from industry experts.
- Chapter 7: Conclusion and Recommendations – summarizes the findings of each of the sections of the study. Some recommendations are provided for optimization of coding and structural grading approaches, along with some ideas for future research works relative to the topic.

Chapter 2: Literature Review

2.1 Introduction

The modern life's quality and standards highly rely on the efficiency of assets and the municipal infrastructure (FCM, 2006). Along with its undeniable dedication to the citizens' satisfaction, the infrastructure plays an important role in economical enhancements. In Canada, most of the infrastructure is constructed and managed by the municipalities. During the past decades, municipalities across the country have been dealing with reduced revenues and shortage of funds. This matter resulted in postponing the required investments and maintenance actions for many years. As a result, a big portion of Canadian infrastructure is just about to fail because of many years of deterioration and improper maintenance, which still follows with the same direction (Mirza, 2007).

Between the 1950's and 1970's Canadian municipalities started to develop their infrastructure. Now after approximately a century the breaking point is imminent. Being a concern of the residents' everyday lives, the impact of infrastructure failure is obvious. Unattended potholes in the pavement, bridges in disrepair, insufficient water treatment and sewer systems are only some examples of the existing infrastructure problems and utilities which are not capable of meeting the demands anymore.

In 1985, the cost of repairing the deteriorating Canadian infrastructure was estimated at approximately $12 billion. Now, having not taken any appropriate action in about 30 years the cost has grown drastically, and has reached $123 billion (Mirza, 2007). This remains a Canadian municipal infrastructure deficit, with a much faster growth rate than what had been previously calculated due to the ongoing neglect that has been permitted. The mentioned deficit has a direct impact on all communities; no matter how big or small the communities, because the municipal governments have no tax base to overcome the growing deficit (FCM, 2006). Municipal governments' share of all tax revenues is shown in Figure 2.1.

Currently municipalities have a hard time managing and controlling infrastructure demands. This condition is a result of ongoing population growth, and the bulk of existing infrastructure left unaddressed, which are now requiring urgent rehabilitation and repairs.

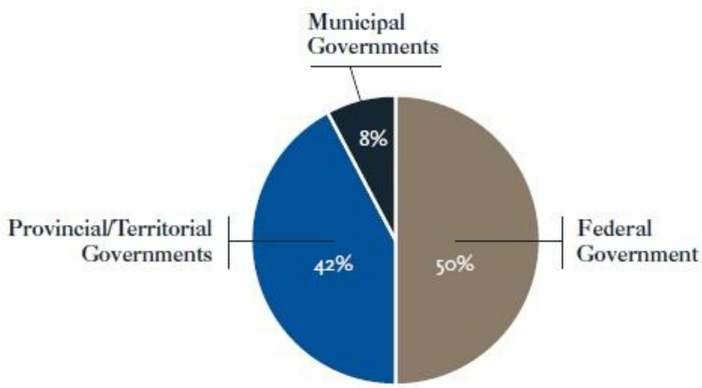

Figure 2.1.Municipal Government Share of All Tax Revenues (FCM, 2006)

Beginning in the mid-50s and continuing for almost twenty years, money spent in infrastructure had a growth of 4.8% per year. This rate kept up with the nation's population growth rate. The infrastructure investment growth then went down to an annual rate of only 0.1%, but the population growth kept its rate. The spending cut to the existing infrastructure since the late 70's, delayed the proper maintenance and gradually created an overwhelming backlog of aged infrastructure in need of rehabilitation.

Two distinct issues are occurring under the municipal infrastructure deficit:

- Unfinanced grants are being offered for enhancing the existing infrastructure run by municipalities,
- Capital is required for fixing and maintaining the assets that are not considered to be even in the lowest satisfactory conditions.

In other words, the deficit is the money that should be paid to prevent assets from deterioration (Mirza, 2007).

2.2 Deficit Compartments

The deficit scope is divided into different categories of municipal infrastructure (Harchauni et. al., 2003):

- Transportation (roads, bridges, sidewalks, curbs),
- Transit systems (facilities, equipment and rolling stock),
- Waste management,
- Water and waste water systems (water distribution, supply, and treatment and sanitary and storm sewers and related treatment facilities),
- Community, Recreational, Cultural and Social Infrastructure.

Figure 2.2 illustrates the municipal infrastructure stock in Canada. Many studies and surveys have been conducted by national institutions and individuals including Canada West Foundation (2003), Canada’s Civil Infrastructure Systems – Technology Road Map Panel (CIS-TRM, 2003), Canadian Council of

Professional Engineers (CCPE, 2005), National Asset Management Working Group (NAMWG, 2009), and Mirza and Haider (2003) address the certain need for establishing a long-term plan to eliminate the infrastructure deficit. The first step for such a plan is an accurate determination of the scope of the deficit. Different levels of Canadian governments are able to include their deficits on their ongoing regular budget. This matter does not apply to municipalities. Therefore, deficits become much easier targets to be postponed with lesser pressure compared with operating capitals. This situation has contributed to the gradual, yet huge growth of municipal infrastructure deficits, which have been differed for decades (Mirza, 2007).

Figure 2.2.Canada's Municipal Infrastructure Stock (Harchauni et. al., 2003)

According to Technology Road Map 2003 – 2013, Canadian infrastructure aging condition is as the following (Figure 2.3):

- 40 years old or less: approximately 41 percent.
- Between 40 and 80 years: approximately 31 percent.
- More than 80 years: approximately 28 percent.

Almost 79 percent of the service infrastructure's life has passed in Canada. This point becomes very important by noticing the fact that asset deterioration rate drastically goes higher as asset ages.

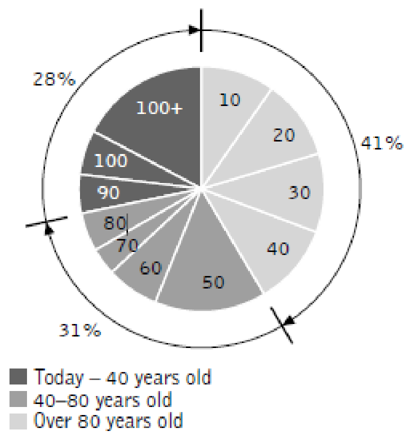

Figure 2.3.Age of Canadian Municipal Infrastructure (CIS-TRM, 2003)

As time goes by, assets deteriorate more and rehabilitation costs to return them back to a minimum standard level are much more than the money needed for having them improved before depreciation. Also, there are cases where infrastructure repair is not possible anymore. In such cases the whole replacement process can cost much more than expected due to dismantling, remains removal, and all the transportation and labor works involved.

2.3 Water and Wastewater Systems

Going back to the deficit categories, it is obvious that water and waste water systems carry a noticeable portion of the total ongoing infrastructure deficit (Harchaoui et. al., 2003). Beyond that, water and wastewater systems are the key elements of the modern civil infrastructure and good resemblance of life standards in any major city. Therefore this section of the infrastructure deserves more attention and higher priorities. Being an important part of each citizen's everyday life, water and sewer systems require more focused and detailed study (NRC, 2004).

Running and managing the water systems in Canada is mainly the responsibility of municipalities. Apparently, this field is the biggest consumer of local governments' spending for over 80 percent of the capital (Harchaoui et. al., 2003). Based on the surveys published by the Canadian Water and Wastewater Association (1998), the required fund for enhancing the available infrastructure in water and wastewater area, in a period of 15 years between 1997 and 2012 would be $88.5 billion. The survey states that the mentioned amount of money hardly makes up for the deterioration which happened to assets only from 1993 to 2002. The growth of different sections of infrastructure in the period of 1996 to 2007 is shown in Figure 2.4.

All the mentioned points are leading to the necessity of repairing water and sewage infrastructure. The main focus also, should be on large and old cities. Despite the huge deficit, aging influence is apparently still neglected and no compensation has been devised yet. Therefore, not only urgent rehabilitation actions are required, but also these actions should be taken under a comprehensive priority allocation system (NAMWG, 2009). Prioritizing comes into account since postponing the segments of the sewer infrastructure with more critical conditions will cause higher costs associated with the rehabilitation plans. Also, there might be a possibility of losing the entire asset due to such issues.

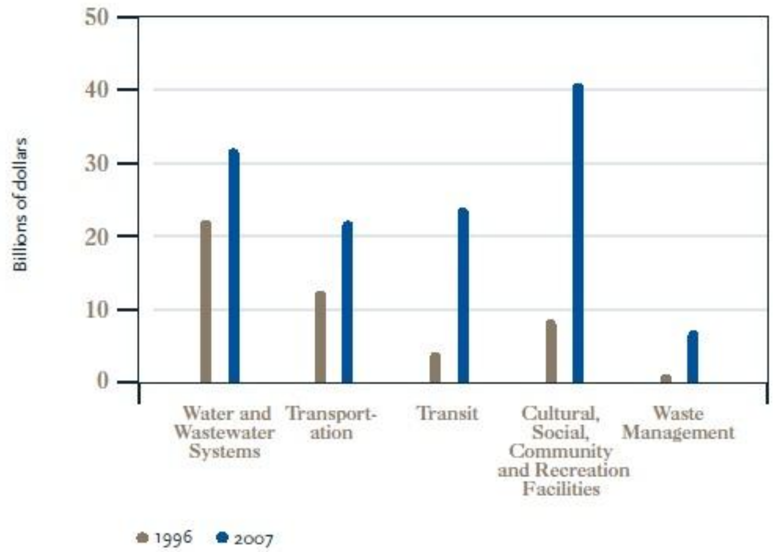

Figure 2.4.Municipal Infrastructure Growth, 1996 to 2007 (Mirza and Haider, 2007)

Hence, the pipelines should be examined and assessed before going through the rehabilitation process so that the pipelines with no minimum acceptable structural conditions are identified and receive higher rehabilitation priorities.

2.4 Water and Wastewater Breakdown Aftereffects

Almost all levels of the society will have to share the consequences of the water and sewer system failure, especially in the large cities. This is why water and wastewater failure is rated critical, with "zero tolerance for failure" in asset management terms (Crowder, 2011). Asset management systems categorize these aftereffects in main and sub-categories, as the following (Bainbridge et. a., 2012):

- Environmental: this might simply be categorized as the most destructive impact of major water and wastewater breakdowns. Sewage biological hazards such as bacteria, viruses, and funguses can easily affect lives of large groups of people in short periods of time. The sub-category for this issue is the damage that environmentally sensitive areas will face.

- Economic and socioeconomic: whenever a major failure happens in the water and wastewater system, different sorts of costs will be imposed on the municipalities. The cost items may directly be related to the rehabilitation of the failed system along with interruptions in providing proper service to the citizens. Indirect costs are brought up as consequences of the failure, such as interruption in the traffic flow and businesses, property damages, and fatalities in some intense cases.
- Operational: this category mainly focuses on the way that responsible organizations bounce back after facing the breakdown of the systems.

2.5 Asset Management

2.5.1 Asset Management Definition

A system, which is used to control and direct the assets that are important to an agency, is titled an asset management system. (Jones and Lewis, 2012). Asset management systems normally use a matrix to implement the system, based on asset's criticality. The matrix of assets' risk factors is shown in Figure 2.5.

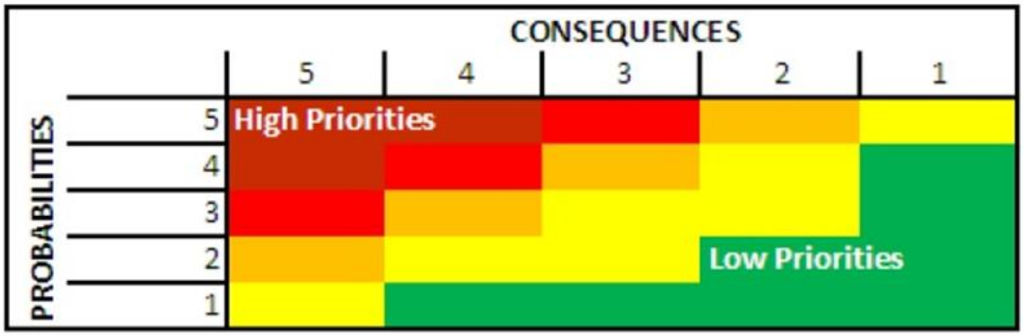

Figure 2.5. Risk Factors Matrix of Assets (Jones and Lewis, 2012)

Items contributing to this criticality are:

- Critical users such as schools and hospitals,
- Significant users such as major industries,
- Asset type, attribute, and location (for instance, a pipeline which is 200 millimeters in diameter and is laid along a highway).

Water and waste water pipelines draw as much attention in each asset management system that the success of the whole system relies on this section of the utilities. The reason for this matter could easily be found in the state of the art, and it lies within the prices that the entire community should pay if something goes wrong (Jones and Lewis, 2012).

2.5.2 Condition Assessment and Protocols

The term "condition assessment" relates to establishing the existing physical condition, identifying the deterioration pattern, and determining the potential of collapse or failure of an asset (NRC, 2004). Condition assessment is a portion of the asset management program, and this matter should follow the established and accepted guidelines which are known as condition assessment protocols or condition assessment systems.

Sewer condition assessment system considers the existing sewer pipelines and sets a milestone for giving maintenance priorities to different pipelines depending on the risks associated with their breakdown.

Condition assessments normally follow a well-defined process consisting of the following steps (Marlow et al, 2007):

- Establishment of condition assessment objectives.
- Asset data collection.
- Inspection of assets.
- Data analysis.
- Decision making.

McDonald and Zhao (2001) suggest an algorithm for condition assessment which is illustrated in Figure 2.6.

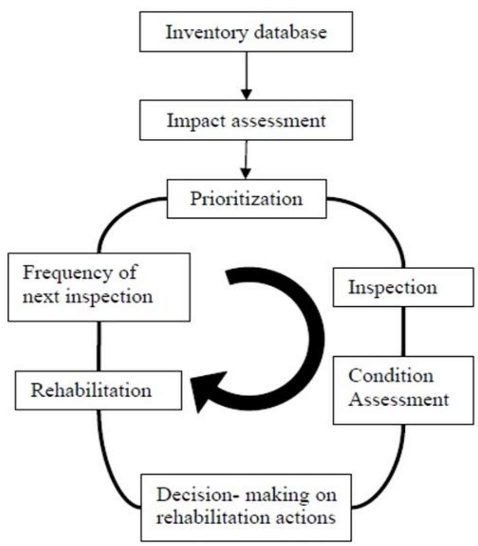

Figure 2.6. Condition Assessment Algorithm (McDonald and Zhao, 2001)

2.5.3 Development of Condition Assessment

Condition assessment programs are developed based on the objectives they have to meet. Feeney et. al. (2009) lists these objectives as:

- Regulatory Compliance.
- Efficiency of Operation and Maintenance.
- Risk Management.
- Budgeting Forecast.

Also, along with the development objectives, goals should be set for the execution of the condition assessment program as well. This step is as important as setting the development objectives, otherwise evaluating the efficiency of the program will not be possible. Examples of the execution goals can be:

- Assessing the structural condition of the asset.
- Determination of asset's deterioration pattern.

Condition assessment program implementation costs should be tracked accurately for both direct and indirect cost items. Having set the program objectives in the first stage of the program development, the profits of the program are figured out. It is possible to compare the costs associated with program implementation, with its expected enhancements. However, it is always more complicated to define the program advantages and benefits in financial figures. Generally, the direct and indirect costs of condition assessment program execution fall into three major categories of field inspections, data analysis and planning, and service interruptions caused by field inspections.

The following list is a few instances of advantages and benefits that a condition assessment program can offer (Feeney et. al, 2009):

- Instant unexpected repair expenses are prevented.
- Major failures and their consequences, such as business interruptions, health and environmental issues.
- Better prioritization and planning for rehabilitative actions.

2.5.4 Condition Assessment Systems Methodologies

The basic concept of sewer condition assessment is to compare the existing situation of a sewer pipeline to a new or like new pipeline, both structurally and operationally. Such comparison results in a numerical grade for asset or a section of it, which precisely depicts the existing condition of asset. The common methodologies for condition assessment systems fall under the following categories (NRC, 2004):

- Subjective Grading:

Basic principles of this assessment method are visual inspection, in site surveys, or professional analysis by an expert. A score represents the grading which is a result of inspected damages to pipeline's physical condition. Utilizing reliable equipment and using experienced reviewers result in an accurate grading.

- Distress-Based Evaluation:

This particular method requires referring to a protocol to determine distresses and analyzing how each condition could influence asset's structure and operational service. Usually deduct values are assigned to each structural or operational defect. The WRc guideline uses this method for assessing sewer infrastructure.

- Non-Destructive Testing:

There is no destruction to asset in this method and is more expensive than previously mentioned methods. Some instances of techniques used for non-destructive testing are thermography methods such as radar, magnetic, acoustic, sonar and infrared, fiber optic sensing, ultrasonic, and ground penetrating radar (GPR).

2.6 Pipeline Inspection Methods

Pipeline management programs look at asset's condition with high sensitivity since in the case of failure, the costs associated with aftereffects on municipal utilities and its users can run high immediately, plus longstanding environmental and health concerns. Since sewer systems are buried under the ground, they may not be ready for inspection all the time. Also, in many old cities municipalities do not have comprehensive asset maintenance records for their old sewer systems. Sewer pipes' attribute information such as location, age, physical properties and the existing conditions of assets are not available (Allouche and Freure, 2002).

If pipeline segments that are not in minimum acceptable conditions are identified and repaired, failure of the entire asset is avoided. Such identification process involves collecting comprehensive information of the pipeline and inspection is a decisive part of it.

The very first modern pipeline inspection methods were utilized after the Second World War (Allouche and Freure, 2002). Since then, lots of techniques have been developed and implemented for underground pipeline inspection to help increase the accuracy and comprehensiveness of data collection. Nowadays, there is a variety of methods available for municipalities to inspect their underground infrastructure. It is important to identify each method's advantages and restrictions so that the results are cost-effective.

Man entry is considered to be the most basic pipeline inspection method. It involves the actual physical data collection of asset by a trained inspector. The cost and danger associated with this method have made it the least attractive method for the clients, along with the high level of potential human errors. Pipeline inspection method is a function of factors like pipeline's material, depth, age, diameter, and most importantly the type of service it delivers. A variety of pipe inspection methods are shown in Figure 2.7. The following section considers those methods which are being utilized to inspect sewer pipes.

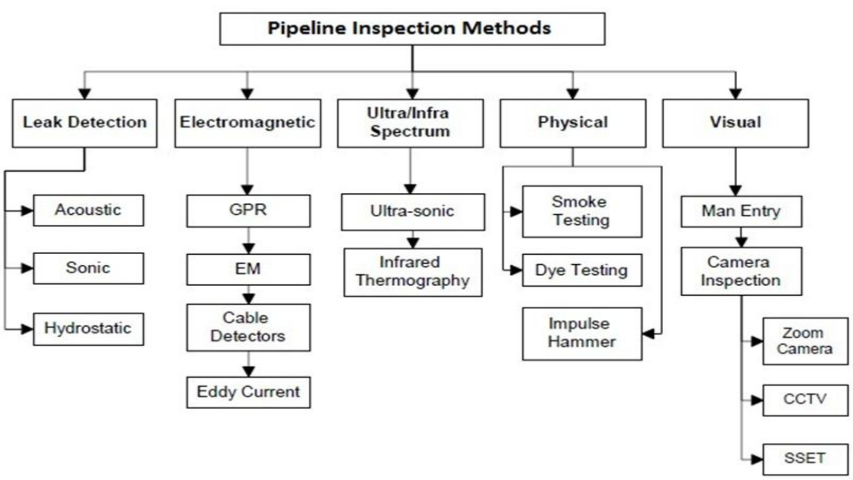

Figure 2.7.Pipeline Inspection Methods (Allouche and Freure, 2002)

2.7 Physical Pipeline Inspection Methods

2.7.1 Smoke Testing

Smoke testing is a sewer pipe inspection method known for its fast process and reasonable cost. It involves occasional man entry and is reliable for identifying leaks in the pipelines. As shown in Figure 2.8, a blower is installed on a manhole entrance and blows the smoke generated from a smoke bomb into the network. Smoke identifies detached joints and cracks along the segment of the pipeline which is isolated prior to the operation, so that the smoke is concentrated enough for that segment (Water Environment Federation 2009).

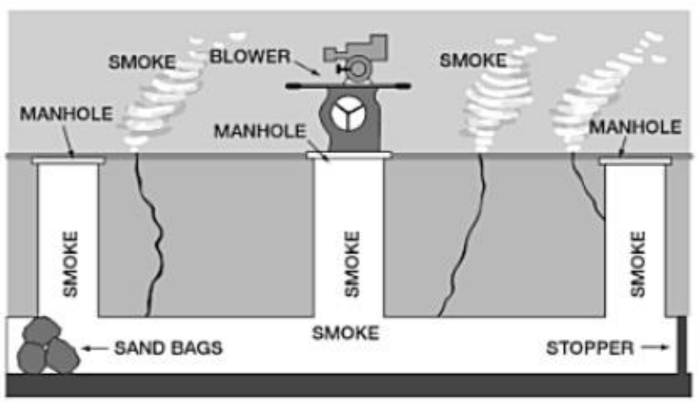

Figure 2.8.Smoke Testing (Water Environment Federation, 2009)

2.7.2 Dye Testing

Dye testing is used to identify where rain or ground water enters the sanitary sewer system. For this purpose, a non-toxic color is used to dye the water and is sent through drain leaders, driveways or local drains. Then, the sanitary sewer manhole in the downstream is inspected to check whether dyed water could be seen or not. This method is very helpful to determine whether a pipe or a part of the network drains or not. If non-toxic dye is used, it is environmentally friendly and will clean up with water with no hazards to the citizens. The dye is usually powdered and is mixed with the fluid. It is carried along the pipe with a visible color for simplicity of monitoring (Water Environment Foundation 2009).

Figure 2.9. Dye Testing (www.bwsc.org)

2.7.3 Impulse Hammer

This method of pipe inspection is mainly for inspection of brick sewers and determines the structural reliability of a pipe. A dynamic hammer is placed at the bottom of a manhole, which sends broadband frequency into the pipeline. The sewer structure reciprocates the frequency and its response is recorded by an accelerometer. The structural evaluation of the sewer pipe is measured relative to the records read from the accelerometer and the hammer (Saibbald et. al., 1995).

Figure 2.10.Impulse Hammer and Accelerometers (www.used-line.com)

2.7.4 Ultra/Infra Spectrum Methods

2.7.4.1 Ultra-sonic

Ultra-sonic is a non-destructive inspection method which provides the opportunity to measure different attributes of the pipelines which other inspection types might not be capable of. Physical inspection methods are not able to record information such as pipe wall thickness, structural defects depth, or the condition of pipe's surrounding area. High measurement accuracy is the biggest advantage of this technology. Ultra-sonic inspection devices send high frequency sounds waves towards the pipeline. The sound comes back to the device, after encountering different objects on its path. Therefore the amount of energy reflected back to the device is not as much as the emission. This variation in the magnitude of energy and its travel time are the requirements for acquiring the different objects' locations (Cascante et. al., 2001). This technology is able to detect most of the existing structural defects in a pipe, such as fractures, cracks, misaligned joints and distorted pipe walls.

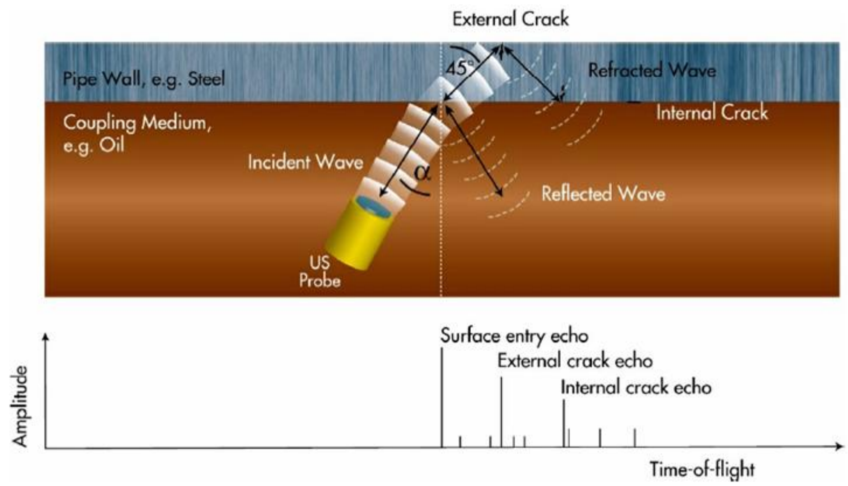

Figure 2.11. Ultra-sonic Inspection for Cracks (www.ppsa-online.com)

2.7.4.2 Infrared Thermography

Thermography studies temperature variations and infrared radiations of an object. It measures the thermal energy flow from the warmer side of an object to the cooler side. The flow is relative to the material and its heat conductivity. The measurement is performed by devices called thermography cameras. The results of measurement are usually demonstrated in images, with different colors assigned to the amount of infrared radiations from the considered objects' surfaces. This technology makes it possible to detect different deficiencies in the pipes such leaking points. Although the defect's severity and exact location of it may not be one hundred percent accurate (Read et. al. 1997). Figure 2.12 illustrates inspection of a pipe segment using infrared thermography.

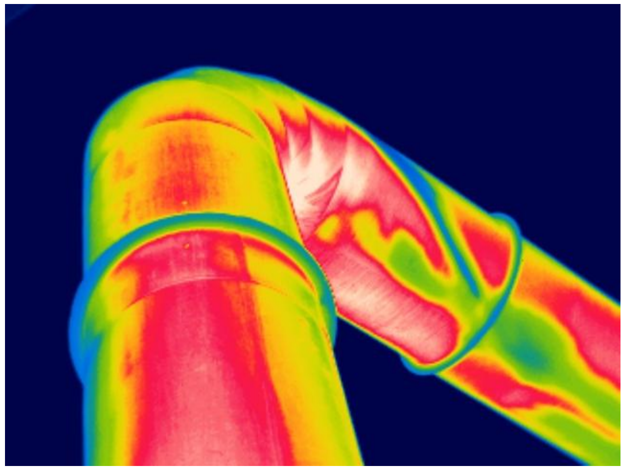

Figure 2.12. Infrared Thermography Inspection (www.maverickinspection.com)

2.7.5 Electromagnetic Methods

2.7.5.1 Ground Penetrating Radar

In this method, radio signals are sent into the ground area under consideration. When the signals are reflected and come back to the radio emission device, the signals' energy and travel time are recorded. The technique has outstanding capabilities in accurate locating of the buried utilities. Recently, ground penetrating radar devices are designed to crawl into repaired pipelines to evaluate the quality of the rehabilitation. Advantages of these devices include their light weight and easy setup, along with accurate reports based on the client needs. However, in order to get the best accuracy and efficiency from the technique, the testing medium should be free from electromagnetic properties so that ground penetrating radar signal could reach its maximum depth of penetration (Mellet 1995).

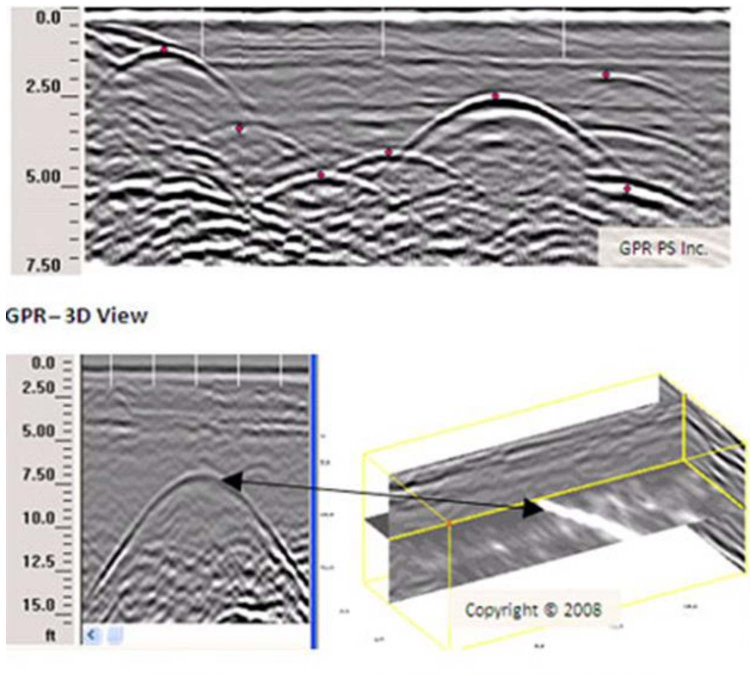

Figure 2.13. Locating Pipelines using Ground Penetrating Radar Technology

(www.gprps.com)

2.7.6 Camera Inspection

2.7.6.1 Closed Circuit Television (CCTV)

In the sewer industry, CCTV is the most convincing tool to inspect the sewer pipes. In this method a robot carries a camera inside the pipe. The robot is steered from a control unit with recording capabilities. An operator manually rides the robot through the pipe from the control unit and should be trained to differentiate between defect types. Whenever the camera reaches a defect, the operator should televise it with more details and provide a close-up shot from the defect. Meanwhile, the operator should document the structural, operational, and constructional observations. Videos should be recorded within a specific range of speed.

The major concern with this technology is its high dependence on the operator's level of experience, since both video recording and documenting the inspections are totally controlled by the operator. Also, high water level and steam inside the pipe will result in undesirable inspection quality.

Figure 2.14. A CCTV Snapshot of a Pipe in Edmonton, Alberta

2.7.6.2 Sewer Scanners and Evaluation Technology (SSET)

SSET was invented in Japan in 1994, to overcome CCTV restraints (ASCE, 2001). In this technology a gyroscope is utilized to determine the pipe's inclination, and a high definition scanner provides a flat image of the entire pipe interior. This 360° picture of the pipe gives the reviewers an opportunity to have a better view of the pipe rather than the image produced by normal CCTV cameras. Another advantage over the traditional CCTV inspection is that the produced image is continuous, therefore there's no need to stop the camera and get a close-up image of the defect while recording the video. Also, since the entire length of pipe is scanned, documenting pipe defects at time of actual inspection is not required.

Figure 2.15. A 360° SSET Image (www.cardiff.ac.uk)

2.8 Condition Assessment Protocols in Canada

The existing internationally accepted condition assessment systems currently being used by Canadian municipalities are listed below:

- Sewerage Rehabilitation Manual (SRM), developed by The WRc in 1980, which is structured based on CCTV inspection. The manual's fourth edition was published in 2004.
- The North American Association of Pipeline Inspectors (NAAPI) compiled a manual on sewer condition assessment in 2004 with the WRc SRM being its main reference.

- The NASSCO established the Pipeline Assessment and Certification Program (PACP) in 2004 in the United States, with assistance from the WRc. This program is considered a standard CCTV-based sewer condition assessment program.

In order to find out about the use of different condition assessment practices in Canadian municipalities, Allouche and Freure ran a survey in 2002. They received responses from 62% of the municipalities to which they had sent their questionnaires. The respondent municipalities had 17% of Canada's population, nearly 5.2 million. According to the survey results, 68% of the attending municipalities had adopted different editions of the WRc SRM for their sewer pipeline assessments. Also, the survey showed that major Canadian municipalities were immediate users of the WRc SRM protocol or developed their own assessment system based on the WRc SRM fundamentals. Many of respondent municipalities employed CCTV operators and reviewers who were certified by NAAPI. NASSCO in the United States developed the PACP to adjust the WRc SRM protocol for North American requirements. These requirements include types of sewer systems and materials that are different than the United Kingdom, along with the different terminology. This section of the study provides a brief description of three major categories of sewer pipe condition assessment standards adopted by Canadian municipalities; The PACP, being the North American edition of the WRc SRM protocol, the fourth edition of the WRc SRM, and municipalities' in-house developed assessment systems, which is the City of Edmonton's sewer assessment protocol in this study.

2.8.1 NASSCO Pipeline Assessment Certification Program (PACP)

The NASSCO of the United States in cooperation with the WRc of the United Kingdom developed the PACP in 2001 based on the third edition of the SRM which was already being used in the United Kingdom since 1980. The PACP coding is very similar to the WRc SRM with some modifications to make it useful in the United States. The most significant changes are made on the terminology to adjust it with the terms used in the North America.

The protocol's coding system consists of several indicators. Either the coding is done for a defect or a feature, the composition is as the following:

- First indicator: this indicates the defect or feature's group, such as structural or operational and may have one or two letters.
- Second indicator: this is called the "descriptor" and provides information related to the direction and location of the defect or feature and might have one or two letters. For instance the descriptor indicates whether a crack is longitudinal, circumferential, multiple, or spiral.
- Third indicator: this indicator is called the "modifier". If required, modifiers give more detailed information on the location/severity of the defect or feature and might have one or two letters. Not all groups of codes require a modifier.

If the camera records a type of defect for over three feet, or if the defect is occurring at certain intervals repeatedly, the defect is considered as "continuous defect". Continuous defects have two categories:

- Truly: the defect is continuous and is inspected to occur with no interruption for more than three feet, such as longitudinal fractures or cracks.
- Repeated: the defect occurs at 75% of its regular intervals. Examples of such continuous defect could be circumferential cracks and open joints.

The PACP divides the structural defects into 12 groups called the structural family, which are briefly described as follows.

2.8.1.1 Crack

A crack is defined as a "visible crack line" on the surface which is not visibly open and pipe pieces are still intact and in place. A crack could be inspected in four shapes. If it runs parallel to the centerline it is considered longitudinal. A crack which runs parallel to the joints is circumferential. A combination of both of the mentioned types is called multiple cracks and if an individual crack changes position as it moves along the pipe is titled spiral by the PACP. Figure 2.16 shows a case of multiple cracks.

Figure 2.16. Crack – Multiple (CM) (PACP, 2001)

2.8.1.2 Fracture

A fracture is originally a crack which has become visibly open, but the sections of pipe wall are still in place and intact. Same as cracks, if it runs parallel to the centerline it is longitudinal, and fracture that is parallel to the joints is circumferential. A combination of longitudinal and circumferential fractures is called multiple fractures and an individual fracture which runs along the pipe and changes position is a spiral fracture.

2.8.1.3 Broken

This defect category refers to a pipe that its pieces are noticeably displaced and have moved from their original position. The displacement must be at least half of the pipe wall thickness according to the defect definition. Usually some deformations accompany the break. If the soil or a void behind the broken piece is exposed and visible certain modifiers are used to describe the situation.

2.8.1.4 Hole

When a pipe segment has a visible hole in its wall, and broken piece has dislodged form the pipe wall, the PACP calls it a hole. Same as broken, if the soil or a void behind the broken piece is exposed and visible certain modifiers will accompany the code. A hole is shown in Figure 2.17.

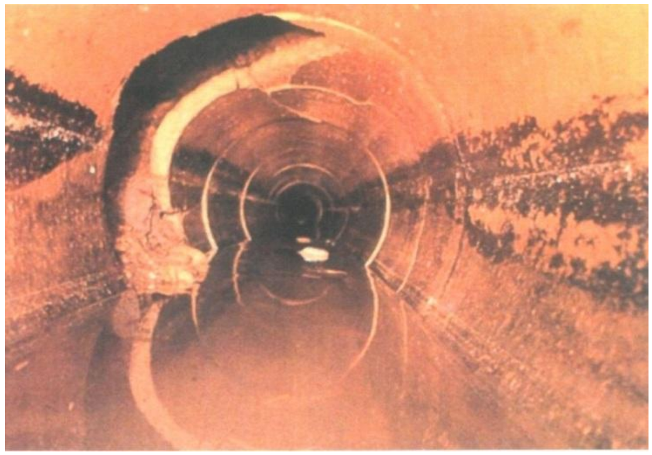

Figure 2.17. Hole (H) (PACP, 2001)

2.8.1.5 Deformed

The PACP defines a deformed pipe when it is damaged to the point that the cross-section of the pipe is noticeably altered. This is the last stage of damage before pipe totally collapses. Deformation without substantial loss of structural integrity in the pipe is also possible.

2.8.1.6 Collapse

When deformation is so great that causes complete loss of structural integrity of the pipe, for about 40% of the cross-sectional area and the camera is blocked, the pipe has collapsed. In such cases, only collapse should be coded, and coding of the individual defects within the collapse is not necessary. Figure 2.18 illustrates an instance of collapsed pipe.

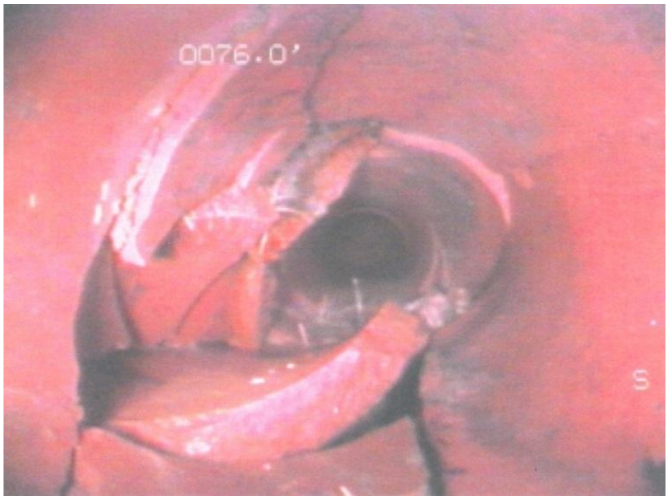

Figure 2.18. Collapsed Pipe (XP) (PACP, 2001)

2.8.1.7 Joint

The PACP divides joint defects into three categories. If spigot is not concentric with the socket of the adjacent pipe the defect is recognized as an offset joint. If adjacent pipes are longitudinally pulled apart at the joint the PACP calls it a separated joint. And finally, when the alignment of the adjacent pipes is not straight an angular joint has occurred. The severity of these defects is determined by comparing the offset or separation distances with the pipe wall thickness in separated and offset joints, and the angle of misalignment for angular joints. Based on these parameters the occurred defects are described as either medium or large.

2.8.1.8 Surface Damage

This group provides description of different failures and damages which are inspected at the inside wall surface of the pipe. These damages may have chemical or physical causes. The PACP describes a slight surface worn by coding it as “increased roughness”, and if the damage is more severe than a slight worn and fines of the pipe material are worn away the code “aggregate visible” is used. When some of the pipe aggregates are missing and small holes appear on the surface of the pipe wall the code used to describe this situation is “aggregate missing” and if small holes grow bigger that the rebar of the pipe material is exposed the code “reinforcement visible” will be used. In cases of not having much aggregates left on the pipe surface and pipe reinforcement is easily visible “reinforcement projecting” describes a more severe situation than the previous stages, and if corrosion is inspected on the rebar it should be labeled with “reinforcement corroded”. In occasions where a hole is inspected during the survey and certainty exists that the hole is caused by erosion or corrosion due to presence of the other mentioned surface damages, the hole is coded by “missing wall”. Sometimes the surface of the pipe is damaged by spalling, which may be accompanied by fractures around the affected area. The code “surface spalling” is used to describe this defect and also, the cause of the spalling should be noted as well; whether it is “mechanical” or “chemical” and if the cause is not recognized at the time of survey it should be noted as “not evident”. If the damage cannot be described by any of the previous codes, the PACP requires recording this condition by noting the defect as “other”. Also, the corrosion of cast iron and ductile iron pipes is simply noted as “corrosion”. A reinforcement corroded case is shown in Figure 2.19.

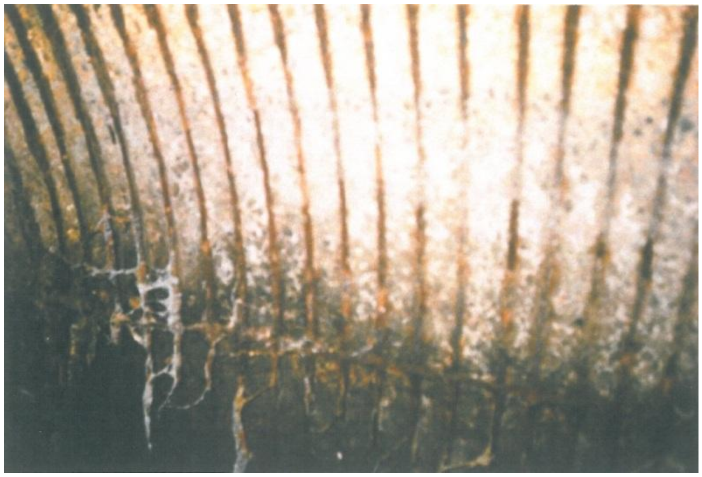

Figure 2.19. Reinforcement Corroded (SRC) (PACP 2001)

2.8.1.9 Lining Failure

The PACP also has a group of structural defects to feature the damages occurred in the pipe segments which are previously rehabilitated by cured-in-place pipe lining method. The host pipe in this category is defined as the original pipe which is rehabilitated. When lining of the pipe is not properly sticking to the host pipe, is coded “detached”. “Defective end” refers to a situation when the end of the lining is not acceptable for the length is long or short, or even it might be wrapped or ragged. Pipe lining which contains pockets and produces a blistering effect is simply coded as “blistered”. Sometimes after cutting the service pipe connection openings, the liner shrinks and therefore the service connection openings are obstructed and meanwhile the host pipe is exposed as well. This defect is recorded as “service cut shifted”, and if too much of the liner is cut for the service connection that some parts of the host pipe remain without lining, the code “overcut service” is used. If lining covers an abandoned connection, the code “abandoned connection” gives the description for this feature. If little of the liner is cut for the service connection, the flow from the service pipe will come into contact with the lining, which may create a defect in the lining in long term. This situation is coded with “undercut service”. An undercut service will also restrict flow in the pipe and possibly cause debris to snag on the liner. “Buckled” refers to the buckling of the pipe lining which usually occurs at the top of a pipe. In the cases where pipe lining is wrinkled, it is coded by “wrinkled” and this is usually seen when the pipe goes around a corner where there is excess material on the inside radius, resulting in wrinkling. If none of the above codes suitable describe the defect of feature of the pipe lining, the code “other” should be used.

2.8.1.10 Weld Failure

This group is used to describe the failures the pipe fabric’s weld, as well as welds that do not have uniform patterns. This group of defects could happen in large diameter plastic spirally wound welded pipes or metallic pipes. If the weld failure is mainly parallel to the axis of the pipe it is a “longitudinal” weld failure, whereas “circumferential” describes a failure around the circumference of the pipe. A combination of longitudinal and circumferential weld failures is described as “multiple”, and finally large diameter plastic spirally wound welded pipes is coded by “spiral”.

2.8.1.11 Point Repair

This group describes the damages and features of parts of the pipeline which have been repaired or replaced. “Pipe replaced” describes a section of pipeline which is replaced as opposed to the complete pipeline rehabilitation between manholes.

The feature where holes, cracks, and fractures are repaired by patching them in the sewer pipe is described by “patch repair”. When the method of repair involves patching holes or cracks in a sewer by placing a small length of lining over the defects inside the pipeline the code “localized pipe-liner” is used. In the cases where none of the mentioned codes could suitably provide a description of the feature “other” is recorded for the feature.

2.8.1.12 Brickwork

This category of the PACP codes are only used in brick sewers. Where single bricks or areas of brick have moved from their original position, it is recorded by the code “displaced”. For areas where single bricks or areas of brick are missing the code “missing” is used. This code applies if more than a quarter of the brick is missing and if less, one of the surface damage codes may be more appropriate. Sewers where the invert section of brickwork has dropped relative to sewer walls, with a pronounced gap of more than 1 inch between invert and wall are noted by “dropped invert”. “Missing mortar” is another code which describes a sewer where the mortar between the brickwork is missing; however the brick is still in place.

2.8.1.13 PACP Condition Grading System

The PACP assigns a grade of one to five to each of the structural defects and features. These grades are defined as:

1-	Excellent	Defect is minor
2-	Good	Defect has just started to deteriorate
3-	Fair	Moderate defect which keeps on deteriorating
4-	Poor	Severe defect that will reach to its worst situation within an expected period of time
5-	Immediate Attention	Defect which should be care taken immediately

Each pipe receives a segment grade score for each of the five grades. The number of defects belonging to each of the grades is recorded and is multiplied by the grade. Then, five segment grades are summed to get the structural pipe rating. Having calculated the structural pipe rating, the rating is used to calculate the pipe structural rating index. This index indicates defect severity distribution. The pipe rating calculated in the previous step should be divided by the number of defects occurred. Using the structural index, the pipe structural condition could be assessed by as below:

1- Failure unlikely in the foreseeable future

2- Pipe unlikely to fail for at least 20 years

3- Pipe may fail in 10 to 20 years

4- Pipe will probably fail in 5 to 10 years

5- Pipe has failed or will likely fail within the next five years

A complete table of the PACP codes, their descriptors, modifiers, and structural grades assigned to them is provided in Appendix A.

2.8.1.14 Grading of the Continuous Defects

When a defect is inspected which affects a long portions of the pipe continuously, The PACP grades it using its own mechanism. By using this approach the length of the defect is divided by “five” to get the equivalent quantity of the defect.

However, the example provided by the protocol only helps the concept be more complicated. It is stated in the example that “a six meter long continuous defect, grade three, should equate to four grade three defects (PACP, 2001).”

In this study, defects with lengths of up to one meter are considered as the equivalent of one meter of defect. For example, a 6.3 meter longitudinal crack is considered as seven meters of longitudinal crack.

2.8.2 The WRc SRM Fourth Edition

The WRc developed its SRM in 1980, and this standard later became the major reference for most of the noticeable efforts for developing sewer condition assessment protocols. The PACP, as mentioned in the previous section is the best instance of such efforts which and is the North American modification of the SRM.

Since 1980, the standard has been revised four times, and the latest edition was published in 2004, with minor changes to the coding system and a whole new approach to the structural rating system.

Because the PACP codes that are described in the previous section are only variations of the WRc SRM4 to suit the American practices and the code definitions and descriptions are exactly same as the PAPC's, a comparison of the codes from the two standards are provided in Table 2.1.

For joints, the SRM4 requires the reviewer to pay extra attention to the joint detachment, therefore if soil is visible from a displaced or open joint it should be coded separately. On the other hand, the PACP considers surface damages in more depth than the SRM4, with eight different types of surface damages.

Table 2.1. Comparison Table of the SRM4 and the PACP Structural Codes

	WRc SRM4		**NASSCO PACP**	
	Code	Description	Code	Description
Cracks	CC	Crack Circumferential	CC	Circumferential Crack
	CL	Crack Longitudinal	CL	Longitudinal Crack
	CM	Crack Multiple	CM	Multiple Cracks
	CS	Crack Spiral	CS	Spiral Crack
Fractures	FC	Fracture Circumferential	FC	Circumferential Fracture
	FL	Fracture Longitudinal	FL	Longitudinal Fracture
	FM	Fracture Multiple	FM	Multiple Fracture
	FS	Fracture Spiral	FS	Spiral Fracture
Broken	B	Broken Pipe	B	Broken Pipe
			BSV	Broken Pipe, Soil Visible
			BVV	Broken Pipe, Void Visible
Hole	H	Hole in Sewer	H	Hole
			HSV	Hole, Soil Visible
			HVV	Hole Void Visible

2.8.2.1 Structural Condition Grading

The fourth edition of SRM assigns grades to the pipeline segments based on the highest deduct value a segment receives. The logic behind this grading system is that a pipe as a structural unit is at its weakest point's conditions.

Table 2.2. SRM4 Structural Grading Thresholds

Computed Grade	Highest Deduct Value
1	Less than 10
2	10 - 39
3	40 - 79
4	80 - 164
5	165+

To take into account the effects of having more than one defect at the same chainage (within 0.1 meters of length) properly, the defects' deduct values are summed. The segment's highest deduct value is then compared with the structural grading thresholds for the final structural grade of the considered pipe segment. The thresholds for different structural grades are provided in Table 2.2. Individual defect deduct values are presented in Appendix B.

2.8.3 The City of Edmonton Sewer Physical Condition Classification Manual & Standard Sewer Condition Rating System Report

In 1996 the City of Edmonton (COE) developed its own sewer rehabilitation standard and coding system based on the WRc 2nd edition (1986) with specific Edmonton modifications. This manual was revised for its structural condition grading and published in 2010 by the City of Edmonton. However, the revised edition has not been implemented by the City of Edmonton yet and the early edition is still being used. The revised edition is reviewed in the following section of this Chapter. The Sewer Physical Condition Classification Manual mainly defines related codes and Condition Rating System Report is used to assess the sewer condition and set the rehabilitation priorities.

The manual categorizes the structural defects in seven groups of cracked pipe, fractured pipe, deformed pipe, joint displacement, open joints, sags, and surface damage. Also, there are four severity levels defined for these categories which are light, moderate, severe, and broken or collapsed. These defect groups are briefly described in this section and the structural grading approach is explained as well.

2.8.3.1 Cracked Pipe

Closed surface cracks have not opened or displaced the pipe wall. “Light” cracks run across the wall of the pipe perpendicular to the pipe axis while “moderate” cracks run along the pipe length parallel to the pipe axis. “Multiple” cracks are a combination of circumferential and longitudinal cracks which may form an alligator pattern.

2.8.3.2 Fractured Pipe

Fractures are cracks which have opened the pipe walls whereby a distance between the cracks is visible or the pipe wall has become displaced. Fractures may be accompanied by infiltration and seepage. The definitions of the severity levels are identical to cracked pipe and include light, moderate, and multiple fractures. The most intense case of a fractured pipe is a “broken pipe” and has occurred when pieces of pipe have broken away entirely. Usually a broken pipe is accompanied by multiple fractures.

2.8.3.3 Deformed Pipe

A pipe is deformed when its cross-section has been altered and is usually accompanied by moderate cracks and fractures. A “deformation light” describes the condition of apparent deformation and minimal loss of cross sectional area, whereas “deformation moderate” is associated with loss in the cross-sectional area. Moderate fractures may be present in this particular occasion and the reduction of the flow area may reach up to 10%. When 10% to 25% of the cross-sectional area of the pipe is restricted, the code “deformation severe” is used and multiple fracturing may be present in the vicinity of the deformation but the pipe stays intact. When less than 75% of the cross-sectional area of the pipe remains, the pipe has collapsed and lost its structural integrity, which is noted as a “collapsed pipe”.

2.8.3.4 Joint Displacement

A displaced joint has occurred when one pipe segment has moved perpendicular to an adjacent pipe segment at the joint, and shows up as a step change in the pipe wall at the joint. The severity of this defect is determined by the loss occurred in the cross sectional area of the pipe. When a visible displacement with a step of less than one pipe wall thickness is inspected it is noted as a “joint displacement light”. “Joint displacement moderate” describes displacement greater than one pipe wall thickness; however, more than 75% of the cross-sectional area of the pipe remains to allow flow to pass. When less than 75% of the cross-sectional area remains to allow flow to pass, a “joint displacement severe” is inspected.

2.8.3.5 Open Joints

An open joint is where the individual pipe segments have separated longitudinally and leave a gap between segments. An "open joint light" is when the adjoining pipe segments have separated a small amount. Generally during inspection, this defect will look similar to a circumferential fracture and the separation is less than 25 millimeters. In an "Open joint moderate" the opening in the joint is obvious and may be accompanied by debris accumulations. Separation is between 25 to and 100 millimeters. "Open joint severe" is a large opening in the joint that is often accompanied by transverse displacement of the pipe and the separation is greater than 100 millimeters.

2.8.3.6 Sags

Sags are most often noticed by the ponding of water at the sag location. Care should be taken to make sure that the ponding is not caused by debris accumulations or other downstream conditions. Sag is considered "light" if water is present when surveying is taking place. When the camera is partially submerged in the water, the situation is coded as "moderate" sag. "Severe" sag is defined when camera is completely submerged during the inspection.

2.8.3.7 Surface Damage

The COE manual defines surface damage as where the inner pipe surface is damaged by spalling, as the result of chemical attack or wear. Slight spalling or wear cases are noted as "light" surface damage. When voids appear and aggregates are exposed in the concrete pipes "moderate" surface damage is recorded and in "severe" surface damage instances deep voids, exposed aggregates, and steel reinforcements are inspected.

2.8.3.8 Physical Condition Rating

The manual assigns deduction values to each structural defect. For each pipe segment the following scores are calculated:

- Total Score = $\sum$ (Deduct Values), is the sum of all defect values along the pipe segment.
- Mean Score = $\frac{\sum \text{(Deduct Values)}}{\text{Total Pipe Segment Length}}$, is the average of defect values along the pipe segment.
- Peak Score = the worst defect deduct value along the pipe segment.

Having calculated total, mean, and peak scores, they are compared to structural grading thresholds. Table 2.3 shows the thresholds and their relevant structural condition grades. The complete structural defect values are also presented in Appendix C.

Table 2.3. COE Structural Rating Thresholds

Total Structural Score	**Mean Structural Score**	**Peak Structural Score**	**Structural Condition Rating**
Less than 100	less than 0.5	less than 1.0	1
100 - 149	0.5 - 0.99	1.0 - 2.0	2
150 - 199	1.0 - 1.49	2.1 - 3.0	3
200 - 249	1.5 - 2.49	3.1 - 5.0	4
250 and greater	2.5 and greater	5.0 and greater	5

2.8.4 The City of Edmonton Structural Condition Rating System, Final Revised Version

This protocol, developed and published by the City of Edmonton in 2010, is an update of the structural grading system explained in the previous section. This edition of the protocol has not been implemented by the City of Edmonton yet. The new features and modifications could be briefly described as below:

- Some new structural major categories and sub-categories are introduced.
- Some of the defect definitions have been modified such as deformation, collapsed pipe, sad, and surface damage.
- Structural defect values have been renewed.
- Structural grading thresholds for peak, mean, and total scores have been revised.

The updated manual consists of 12 major structural defect categories and 32 sub-categories. Cracks, joint displacements, and surface damages remained with no changes and are identical to the old edition definitions. Broken and collapsed pipes have become separate major categories and are no longer sub-categories of fractures and deformations respectively. However, collapsed pipe has not been revised and the same definition of the previous edition is used for its description. Other sub-categories of fractures and deformations are identical to the old edition's fractured and deformed pipes. Open joint moderate has been removed from the sub-categories of open joints and the other two have not been changed. Same situation exists for sags, that moderate sag is no longer recognized as a defect and light and severe sags are coded in the surveys. New categories are briefly explained in the following sections.

2.8.4.1 Broken Pipe

Broken pipe is defined as fractured pipe where the pieces of the pipe are noticeably displaced or shifted to at least half of the pipe wall thickness. There is often some deformation accompanying the break. “Spalling broken pipe” is spalling that occurs in the pipe wall but the pipe wall has not been fully penetrated. “No-void broken pipe” is the code which is used to describe the pipe wall which has been fully penetrated but no voids are visible. If a visible void exists which is less than one quarter of the pipe diameter and the soil is visible beyond the void, “light void broken pipe” is the code that should be recorded in the inspection. In the case of having a void greater than one quarter of the pipe diameter “severe void broken pipe” is used to describe the defect. Figure 2.20 illustrates instances of severe void broken pipe.

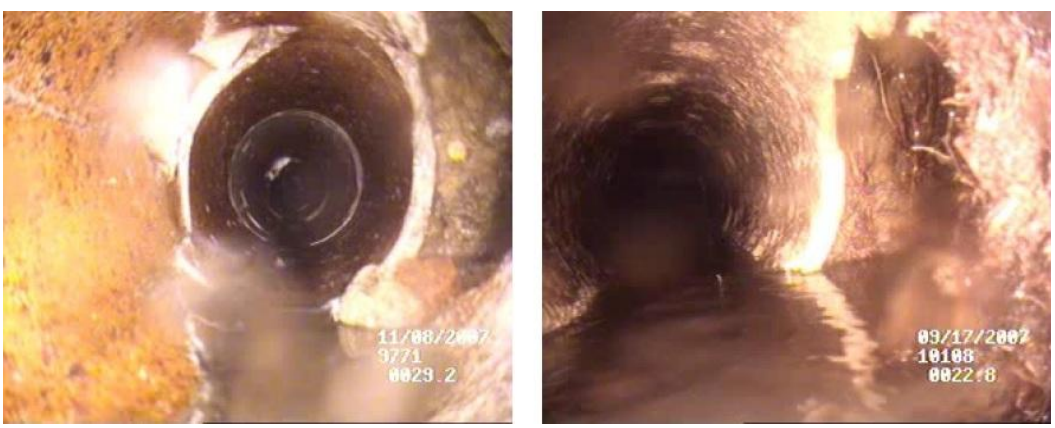

Figure 2.20. Severe Void Broken Pipe (COE, 2010)

2.8.4.2 Hole

A hole occurs in a sewer pipe when a small section of the pipe is dislodged from the pipe wall. If the hole is less than one quarter of the pipe diameter and soil is visible beyond the hole, “light hole” describes the defect, whereas “severe hole” is a hole greater than one quarter of the pipe diameter. It is important to notice that the codes used to describe holes, are identical to light void broken pipe and severe void broken pipe which were defined under broken pipe category.

2.8.4.3 Lining

Lining defects are created or developed due to the improper installation of cured-in-place pipe liners which are used to rehabilitate a defective pipe. Where pipe lining covers an abandoned connection, the code used is “lining with abandoned connection”. In the condition that some parts of the pipe at the service connection is exposed without lining the code “lining with overcut service” is entered in the inspection report. “Lining with undercut service” describes the condition where the liner at the service connection is not fully cut. Therefore the flow and debris acting on the liner may damage the liner in long term. “Wrinkled lining” refers to lining that has a wrinkled effect. It generally occurs at the inside radius of a pipe bend where excess material is used or shrinkage of the lining happens. If none of the mentioned defect codes could describe the inspected lining-related defect, the code “lining – other defects” should be used.

2.8.4.4 External Pipe

External pipe in a sewer occurs when a pipe intrudes through the pipe wall of a pipe.

2.8.4.5 Structural Deduct Values and Condition Grading Calculation

Determination of the structural condition rating of a sewer pipe is carried out in two steps. Using Table 2.4, the structural condition grading of the defects are determined in the first step of the assessment, and defect deduct values are used for the second step.

The structural condition grading for sewer pipes is determined using the following scores and the threshold values for the five structural ratings as shown in Table 2.5.

- Total Score: Sum of all defect weights along the pipe.
- Mean Score: Sum of the defect weights along the pipe divided by the pipe total length.
- Peak Score: Worst condition rating along the pipe.

The process of determining the structural condition rating of sewer pipes includes two steps:

- Step 1: Determine the peak score of sewer pipe and select the sewer pipes with a structural condition rating of four and five for rehabilitation.
- Step 2: Identify sewer pipes which may have a structural condition rating of four and five due to the impact of multiple defects, using Table 2.4 as a guide and then calculate the total and mean scores to confirm the potential

structural condition rating of the sewer pipe by comparing the calculated scores to the thresholds defined by the manual, as shown in Table 2.5. The second step is mainly used to capture sewer pipes with a potential higher structural condition rating of four and five.

Table 2.4. COE Modified Structural Defect Scores and Multiple Values

Defect	SR	Range	Weight	3	4	5
CL - Crack Light	1	1 - 29	10	71%	95%	100%
HL - Surface Damage Light			21	69%	95%	100%
OL - Open Joint Light			25	75%	95%	100%
JL - Joint Displacement Light			28	53%	90%	100%
FL - Fracture Light	2	30 - 39	33	36%	70%	95%
DL - Deformation Light			34	41%	75%	95%
CM - Crack Moderate			37	46%	75%	100%
FXL - Broken Pipe	3	40 - 69	41		71%	100%
HM - Surface Damage Moderate			53		43%	80%
CS - Crack Severe			54		27%	53%
SL - Sag Light			59		27%	55%
JM - Joint Displacement Moderate			62		97%	100%
FM - Fracture Moderate			68		17%	31%
DM - Deformation Moderate	4	70 - 85	70			30%
OS - Open Joint Severe			72			28%
FXM - Broken Pipe			73			25%
SS - Severe Sag			76			11%
HS - Surface damage Severe			76			31%
JS - Joint Severe			79			66%
FS - Fracture Severe			85			6%

Table 2.5. COE Modified Structural Thresholds

Total Score	Mean Score	Peak Score	SR
150	10	10 - 29	1
258	23	30 - 39	2
608	46	40 - 69	3
1717	240	70 - 85	4
> 1717	> 240	86 - 100	5

Chapter 3: Qualitative Comparison of Structural Coding and Condition Grading Systems

3.1 Introduction

One of the main applications sewer pipe condition assessment protocols is to provide a description of the defects inspected in each survey. This description includes the type of the defect, its location, magnitude, and occasionally cause of the defect. Pipe segments are structurally rated based on the codes which are recorded while the segment is inspected.

Each protocol has its own approach to describe and code the structural defects, and the difference between the existing protocols starts at this point. One protocol may consider a particular defect type with more details than others. Surface damages in the PACP are good examples of this point. The PACP defines nine sub-categories for surface damages. The causes for the damages should be noted in the reports as well, whereas the WRc SRM4 and both early and modified editions of the City of Edmonton's protocol only consider three sub-categories for surface damage based on the severity of the damage. On the other hand, the City of Edmonton's protocols consider "sag" as a structural defect. The loss of soil under the pipe for different reasons causes the pipe to drop downwards and this phenomenon is referred to as sag. The WRc SRM and the PACP do not consider "sag" as a separate structural defect category.

In this section of the study, structural codes and coding systems of the considered condition assessment protocols are qualitatively compared with each other by using the descriptive features they provide for the structural codes. This comparison is essential for two reasons:

- Understanding the quality of the description provided by each of the coding systems for the inspected defects during each survey. This description consists of the type, the location, and severity of the defect.
- Finding the equivalent of one protocol’s defect codes in the other protocols. Such mapping provides the possibility of generating automatic pipeline inspection reports using any desired coding system. This feature ultimately results in a practical comparison of the four structural grading systems.

In this chapter, each major category and its sub-categories of defect codes which the PACP, the SRM4, and both early and modified editions the COE have in common are studied. The base code is selected from the PACP and its possible equivalent codes in the three other protocols are sought. This protocol is selected because it defines more number of structural defect codes than the SRM4 and the two editions of the COE. Structural defect categories which are not in common between the four protocols are also introduced.

3.2 Qualitative Comparison of Structural Defect Codes

3.2.1 Coding Cracks Using the Four Protocols

The first sub-category of this group is longitudinal crack (CL) which by definition runs approximately along the axis of the sewer and is parallel to the centerline.

Since the PACP uses the same terminology as the SRM for the most part, the exact same code exists in the SRM4 with the identical definition (CL – Crack Longitudinal). Both editions of the City of Edmonton protocol use a different code for almost the same definition. For a crack that runs along the pipe, the COE editions state that the crack that is generally longitudinal and appears to propagate along the pipe length is entitled as moderate crack (CM).

Circumferential crack (CC) is the type of crack which according to PACP runs approximately at right angles to the axis of sewer and is parallel to the joint. SRM4 uses the same terminology and definition for this sub-category (CC – Crack Circumferential). The code for a general circumferential crack which runs across the pipe wall of pipe, perpendicular to the pipe axis is light crack (CL) in both of the early and modified editions of the COE. Similar to longitudinal cracks, proper equivalents exist for circumferential cracks in all four standards.

The next sub-category to consider is the combination of longitudinal and circumferential cracks that are titled multiple cracks (CM) by both PACP and SRM4. Both editions of COE title such defects as severe cracks (CS) which has an alligator pattern appearance.

Individual cracks which change position as they travel along the pipe, are coded as spiral cracks (CS) by the PACP and the SRM4. However, the COE editions do not consider a separate code for this type of cracking and relative to the position and direction of the cracking, code it as either circumferential or longitudinal crack. It is important to notice that this type of cracking is different than circumferential or longitudinal cracking in essence. Spiral cracking is an indication of torsion in the pipe caused by poor installations or changes in the bedding and support conditions, which may ultimately result in the pipe's failure. Table 2.1 summarizes the characterizing of crack sub-categories using all four standards.

Table 3.1. Characterization of "Crack" sub-categories using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
CL	Longitudinal Crack	CL	Crack Longitudinal	CM	Crack Moderate	CM	Moderate Crack
CC	Circumferential Crack	CC	Crack Circumferential	CL	Crack Light	CL	Light Crack
CM	Multiple Crack	CM	Crack Multiple	CS	Crack Severe	CS	Severe Crack
CS	Spiral Crack	CS	Crack Spiral	-	-	-	-

3.2.2 Coding Fractures Using the Four Protocols

The category of fractures refers to cracks which developed deterioration. Fracture definitions are identical to cracks by the four protocols. The characterizing of the fracture sub-categories is summarized in Table 3.2.

Table 3.2. Characterization of "Fracture" sub-categories using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
FL	Longitudinal Fracture	FL	Fracture Longitudinal	FM	Fracture Moderate	FM	Moderate Fracture
FC	Circumferential Fracture	FC	Fracture Circumferential	FL	Fracture Light	FL	Light Fracture
FM	Multiple Fracture	FM	Fracture Multiple	FS	Fracture Severe	FS	Severe Fracture
FS	Spiral Fracture	FS	Fracture Spiral	-	-	-	-

3.2.3 Coding Broken Pipes Using the Four Protocols

The PACP defines different scenarios for a broken pipe (B). When the pieces are noticeably displaced and have moved from their original position for at least half of the pipe thickness accompanies with some deformation, the pipe is considered as broken. The severity of the defect would cause the defect to receive different deduction values and it is measured by the number of clock positions which is recorded for the defect. The PACP denotes extra modifiers for the code if the soil or a void is visible beyond the defect (BSV – Broken Soil Visible, BVV – Broken Void Visible). The reason for this is to give the highest deduction score to the defect for grading purposes, regardless of the defect's size. On the other hand, the SRM4 only records the defect (B) and since the pipe is structurally intact the size of the defect does not make a significant difference in its structural rating. The early edition of the COE categorizes broken as a sub-category of fracture and records it when the pipe pieces are broken away and is usually associated with multiple fractures (FX). The modified edition of the COE, considers different cases based on the presence of a void in the vicinity of the broken zone. When spalling occurs in the pipe wall but the pipe is not fully penetrated, it is coded as "spalling broken pipe" (FXL). This code can be an equivalent for the code "Broken" in the PACP and SRM4 protocols in which neither the soil beyond the defect is visible nor a void. When the pipe wall is fully penetrated but no voids are visible, the COE's modified edition codes it as "no void broken pipe" (FXM). From this definition and also the pictures provided in the standard it could be concluded that this code is an equivalent of the PACP's "broken soil visible". Figure 3.1 illustrates an example of a broken pipe which is considered as a no void broken pipe using the COE's modified edition.

Figure 3.1.No Void Broken Pipe (COE, 2010)

“Light void broken pipe” and “severe void broken pipe” also could be the equivalents of the PACP’s “broken soil visible. The first code describes a visible void in which the soil is visible beyond the void and the void is less than one quarter of the pipe diameter (FXVL), and the latter has a visible void greater than one quarter of the pipe diameter (FXVS). Table 3.3 summarizes the discussion for the broken sub-category.

Table 3.3. Characterization of "broken" sub-categories using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
B	Broken	B	Broken	FX	Broken	FXL	Spalling Broken Pipe
BSV	Broken Soil Visible					FXM	No Void Broken Pipe
BVV	Broken Void Visible					FXVL	Light Void Broken Pipe
						FXVS	Severe Void Broken Pipe

3.2.4 Coding a Hole in the Pipe Using the Four Protocols

The PACP codes a pipe which has a visible hole in the pipe wall as a “hole” (H). In this case often the broken pipe has completely dislodged from the pipe wall. When the soil is visible beyond the defect extra modifiers are added to the code

(HSV), similar to the cases when a void is visible beyond the defect (HVV). The SRM4 only records the defect and its size (H). If the radial extent of the hole is smaller than one quarter of the pipe diameter, the defect receives a lower deduct value with respect to a defect larger than one quarter of the pipe diameter. The early edition of the COE does not consider a hole as a separate defect, since a hole is usually associated with broken pieces or a collapsed pipe. In the modified edition of the protocol a hole is recorded based on its size. If a hole is less than one quarter of the pipe diameter and the soil is visible beyond the hole, it is coded as “light hole” (FXVL), and if the hole is larger than one quarter of the pipe diameter the code is “severe hole” (FXVS). The codes used to denote a hole in the COE’s modified edition are exactly identical to the protocol’s codes which describe the more severe cases of a broken pipe. The point could be considered as a flaw, since these codes are already defined in another sub-category. The modified edition of the COE’s light hole could be considered as an equivalent for PACP’s hole soil visible and respectively severe hole could be compared with hole void visible. Table 3.4 provides a summary for the hole defect and its sub-categories.

Table 3.4. Characterization of "hole" sub-categories using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
H	Hole	H	Hole	-	-	FXVL	Light Void Broken Pipe
HSV	Hole Soil Visible						
HVV	Hole Void Visible					FXVS	Severe Void Broken Pipe

3.2.5 Coding a Deformed Pipe Using the Four Protocols

When the pipe is damaged to the point that its original cross-section is noticeably altered, the PACP codes it as “deformed” (D). This is the last stage of the damage before collapse. The percentage of deformation should also be recorded at the time of the survey for grading purposes. The PACP requires noticing whether the deformation has reduced the cross-sectional area of the pipe by less than 10% or more than that. The SRM4 uses a more detailed recording and requires recording if the deformation causes up to 5% of cross-sectional area reduction, or more. The early edition of the COE divides the deformation into four sub-categories. The first category characterizes the first stage of damage: light deformation (DL) which is a minimal loss of the cross-sectional area of the pipe. A “moderate deformation” (DM) is defined to have up to 10% reduction in flow area “Severe deformation” will occur when 10 to 25% of the cross-sectional area of the pipe is restricted. The last stage of the COE’s definition for a deformed pipe is a collapsed pipe which will be considered in a separate category in Section 3.2.6. The modified edition of the COE is identical to its predecessor for the deformation category. Table 3.5 summarizes the deformed pipe category.

Table 3.5. Characterization of "Deformation" sub-categories using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
D (<10%)[1]	Deformed	D (0-5%)	Deformed	DL	Deformation Light	DL	Light Deformation
		D (5-10%)		DM	Deformation Moderate	DM	Moderate Deformation
D (≥10%)		D (>10%)		DS	Deformation Severe	DS	Severe Deformation

3.2.6 Coding a Collapsed Pipe Using the Four Protocols

When the deformation is so large that the structural integrity of the sewer is completely lost (more than 40% of cross-sectional area is lost), the PACP defines the defect zone as “collapsed” (X). The same definition exists in the SRM4’s protocol. The COE editions consider a pipe as collapsed when 25% of the cross-sectional area is lost. This can still be considered as equivalents for the collapsed pipe in other two standards. Table 3.6 illustrates the code similarities for this category in the four protocols.

Table 3.6. Characterization of "collapse" category using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
X	Collapse	X	Collapse	XP	Collapsed Pipe	XP	Collapsed Pipe

3.2.7 Coding a Joint Defect Using the Four Protocols

The PACP combines all the defects which are related to the pipe joints into one major category. The first class of this category is offset or displaced joint where

[1] Percentage of cross-sectional area loss

the spigot is not concentric with the socket or ball of the adjacent pipe. The severity of this defect is established based on the pipe wall thickness. If the displacement is greater than one and up to 1.5 times the pipe wall thickness, the code used to record the defect is "joint offset medium" (JOM). For displacements greater than 1.5 times the pipe wall thickness the PACP would use the code "joint offset large" (JOL).

The SRM4 codes a medium displaced joint as "displaced joint medium" (JDM) and respectively a large joint displacement is coded "displaced joint large" (JDL). The SRM4 considers a more severe level of joint displacement where the soil is exposed and visible beyond the joint. This case is not considered by the PACP. It could be concluded that the PACP's definition for a large offset joint could cover this particular code since it includes all displacements greater than 1.5 times the pipe wall thickness.

Both editions of the COE consider slight displacement of a joint to be a structural defect and code it as "light joint displacement" (JL). This code has no equivalent in any of the other two protocols. The definition for this code is a visible displacement with a step less than one pipe wall thickness. A "moderate joint displacement" (JM) as a joint which is displaced greater than one pipe wall thickness and meanwhile, more than 75% of the cross-sectional area of the pipe remains to allow for the flow. This definition covers the PACP and the SRM4's definitions for their medium offset joint and can be considered as an equivalent for that structural code. Both editions of the COE define a "severe joint displacement" (JS) as a joint with a displacement of more than 25% of the cross-sectional area. This definition is not an exact equivalent of the PACP's JDL, but it certainly covers the PACP's definition for severe cases of joint displacements. Table 3.7 is a summary of the codes for the offset joint sub-category from all four protocols.

Table 3.7. Characterization of "displaced joint" sub-category using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
JOM	Joint Offset Medium	JDM	Joint Displaced Medium	JM	Joint Displaced Moderate	JM	Displaced Joint Moderate
JOL	Joint Offset Large	JDL	Joint Displaced Large	JS	Joint Displaced Severe	JS	Displaced Joint Severe
JOL	Joint Offset Large	JDSV	Joint Displaced Soil Visible	JS	Joint Displaced Severe	JS	Displaced Joint Severe

Another sub-category which the PACP defines as a structural defect for the pipe joints is open or separated joints where adjacent pipes are longitudinally pulled apart at the joint. Similar to the offset joints, two severity levels are defined for separated joints: medium and large (JSM & JSL respectively). A medium separated joint is greater than one pipe wall thickness and smaller than or equal to 1.5 times the pipe wall thickness. A large separation is greater than 1.5 pipe wall thickness.

The SRM4 characterizes this defect as open joint, and unlike the PACP divides in into three levels of severity. The first two levels: the "Open joint medium" (OJM) and "open joint large" (OJL) are the exact equivalents for medium and large separated joint from the PACP. While the "open joint soil visible" is the code which describes the condition where two adjacent pipes are totally detached and the soil beyond the joint is exposed and visible. This level of severity could be covered by the PACP's open joint large, since the exposed soil could be visible when the separation is a lot larger than 1.5 times the pipe wall thickness.

Both editions of the COE define a sub-category of separated joint for very small magnitudes of separation. A "light open joint" (OL) occurs when the adjoining pipe segments have separated less than 25 millimeters. This amount of separation does not have a clear equivalent in the other two protocols. The first edition of the COE's protocol defines a "moderate open joint" (JM) for when the opening is obvious and the separation is between 25 to 100 millimeters. This definition covers the definitions for both medium and large open joints from the PACP. The modified edition no longer considers moderate open joints and only considers the separation more than 100 millimeters. This is coded as "severe open joints" (OJ) in both editions. The discussion for open joints is summarized in Table 3.8.

None of the protocols except for the PACP define a code for transverse displacement of the pipes. The PACP defines this defect as "angular joint". Again this code has no equivalent in the other three protocols.

Table 3.8. Characterization of "separated joint" sub-category using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
JSM	Joint Separated Medium	OJM	Open Joint Medium	OM	Open Joint Moderate	-	-
JSL	Joint Separated Large	OJL	Open Joint Large	OS	Open Joint Severe	OS	Severe Open Joint
JSL	Joint Separated Large	OJSV	Open Joint Soil Visible	OS	Open Joint Severe	OS	Severe Open Joint

3.2.8 Coding Surface Damages Using the Four Protocols

All of the four protocols have defined a category for surface damage defects. However, their approaches in coding the defects are very different. The PACP defines a wide range of defects including numerous descriptive details. True realization of the causes of the defects is also important in recording the defects following the PACP. The SRM4 only considers the severity level of the surface damages to record them. This approach is adopted in both editions of the COE's protocol as well. Therefore, finding the equivalents of the codes for surface damages in the other two coding systems is not possible only based on defects' definitions. This matter could be achieved by considering how severe each defect code is in each of the coding systems. Using the deduct values which are assigned to the defect codes, Table 3.9 for surface damage sub-categories is generated.

Table 3.9. Characterization of "surface damage" category using the four protocols

PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
SRI	Roughness Increased	SWS	Surface Wear Slight	HL	Surface Damage Light	HL	Light Surface Damage
SSS	Surface Spalling						
SCP	Corrosion						
SAV	Aggregate Visible	SWM	Surface Wear Moderate	HM	Surface Damage Moderate	HM	Moderate Surface Damage
SAP	Aggregate Projecting						
SAM	Aggregate Missing						
SRV	Reinforcement Visible	SWL	Surface Wear Large	HS	Surface Damage Severe	HS	Severe Surface Damage
SRP	Reinforcement Projecting						
SRC	Reinforcement Corroded						
SMW	Missing Wall						

Table 3.10 illustrates the equivalent of the PACP's codes in the SRM4, the early edition of COE, and the modified edition of the COE respectively.

Table 3.10. Characterization of Equivalent Structural Codes between the Four Protocols

CRACKS							
PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
CL	Longitudinal Crack	CL	Crack Longitudinal	CM	Crack Moderate	CM	Moderate Crack
CC	Circumferential Crack	CC	Crack Circumferential	CL	Crack Light	CL	Light Crack
CM	Multiple Crack	CM	Crack Multiple	CS	Crack Severe	CS	Severe Crack
CS	Spiral Crack	CS	Crack Spiral	-	-	-	-
FRACTURES							
PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
FL	Longitudinal Fracture	FL	Fracture Longitudinal	FM	Fracture Moderate	FM	Moderate Fracture
FC	Circumferential Fracture	FC	Fracture Circumferential	FL	Fracture Light	FL	Light Fracture
FM	Multiple Fracture	FM	Fracture Multiple	FS	Fracture Severe	FS	Severe Fracture
FS	Spiral Fracture	FS	Fracture Spiral	-	-	-	-
BROKEN							
PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
B	Broken	B	Broken	FX	Broken	FXL	Spalling Broken Pipe
BSV	Broken Soil Visible					FXM	No Void Broken Pipe
BVV	Broken Void Visible					FXVL	Light Void Broken Pipe
						FXVS	Severe Void Broken Pipe

Table 3.10. Characterization of Equivalent Structural Codes between Protocols, Cont'd

<table>
<tr><td colspan="8">HOLE</td></tr>
<tr><th colspan="2">PACP</th><th colspan="2">SRM4</th><th colspan="2">COE Early Ed.</th><th colspan="2">COE Modified Ed.</th></tr>
<tr><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td></tr>
<tr><td>H</td><td>Hole</td><td rowspan="3">H</td><td rowspan="3">Hole</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="2">FXVL</td><td rowspan="2">Light Void Broken Pipe</td></tr>
<tr><td>HSV</td><td>Hole Soil Visible</td></tr>
<tr><td>HVV</td><td>Hole Void Visible</td><td>FXVS</td><td>Severe Void Broken Pipe</td></tr>
<tr><td colspan="8">DEFORMATION</td></tr>
<tr><th colspan="2">PACP</th><th colspan="2">SRM4</th><th colspan="2">COE Early Ed.</th><th colspan="2">COE Modified Ed.</th></tr>
<tr><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td></tr>
<tr><td rowspan="2">D (<10%)</td><td rowspan="3">Deformed</td><td>D (0-5%)</td><td rowspan="3">Deformed</td><td>DL</td><td>Deformation Light</td><td>DL</td><td>Light Deformation</td></tr>
<tr><td>D (5-10%)</td><td>DM</td><td>Deformation Moderate</td><td>DM</td><td>Moderate Deformation</td></tr>
<tr><td>D (≥10%)</td><td>D (>10%)</td><td>DS</td><td>Deformation Severe</td><td>DS</td><td>Severe Deformation</td></tr>
<tr><td colspan="8">COLLAPSE</td></tr>
<tr><th colspan="2">PACP</th><th colspan="2">SRM4</th><th colspan="2">COE Early Ed.</th><th colspan="2">COE Modified Ed.</th></tr>
<tr><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td></tr>
<tr><td>X</td><td>Collapse</td><td>X</td><td>Collapse</td><td>XP</td><td>Collapsed Pipe</td><td>XP</td><td>Collapsed Pipe</td></tr>
<tr><td colspan="8">DISPLACED JOINTS</td></tr>
<tr><th colspan="2">PACP</th><th colspan="2">SRM4</th><th colspan="2">COE Early Ed.</th><th colspan="2">COE Modified Ed.</th></tr>
<tr><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td><td>Code</td><td>Definition</td></tr>
<tr><td>JOM</td><td>Joint Offset Medium</td><td>JDM</td><td>Joint Displaced Medium</td><td>JM</td><td>Joint Displaced Moderate</td><td>JM</td><td>Displaced Joint Moderate</td></tr>
<tr><td>JOL</td><td>Joint Offset Large</td><td>JDL</td><td>Joint Displaced Large</td><td>JS</td><td>Joint Displaced Severe</td><td>JS</td><td>Displaced Joint Severe</td></tr>
<tr><td>JOL</td><td>Joint Offset Large</td><td>JDSV</td><td>Joint Displaced Soil Visible</td><td>JS</td><td>Joint Displaced Severe</td><td>JS</td><td>Displaced Joint Severe</td></tr>
</table>

Table 3.10. Characterization of Equivalent Structural Codes between Protocols, Cont'd

SEPARATED JOINTS							
PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
JSM	Joint Separated Medium	OJM	Open Joint Medium	OM	Open Joint Moderate	-	-
JSL	Joint Separated Large	OJL	Open Joint Large	OS	Open Joint Severe	OS	Severe Open Joint
JSL	Joint Separated Large	OJSV	Open Joint Soil Visible	OS	Open Joint Severe	OS	Severe Open Joint
SURFACE DAMAGES							
PACP		**SRM4**		**COE Early Ed.**		**COE Modified Ed.**	
Code	Definition	Code	Definition	Code	Definition	Code	Definition
SRI	Roughness Increased	SWS	Surface Wear Slight	HL	Surface Damage Light	HL	Light Surface Damage
SSS	Surface Spalling						
SCP	Corrosion						
SAV	Aggregate Visible	SWM	Surface Wear Moderate	HM	Surface Damage Moderate	HM	Moderate Surface Damage
SAP	Aggregate Projecting						
SAM	Aggregate Missing						
SRV	Reinforcement Visible	SWL	Surface Wear Large	HS	Surface Damage Severe	HS	Severe Surface Damage
SRP	Reinforcement Projecting						
SRC	Reinforcement Corroded						
SMW	Missing Wall						

3.2.9 Unique Defect Categories

Each of the protocols defines some categories of defect which are not common among the other standards. These categories may address certain local needs which are not considered important in the origin place of other protocols. For instance, the PACP has a separate section for brick sewers, which are not used in

Edmonton or many other Canadian cities. Further, external objects in sewers is an issue which should be addressed by the protocol which is adopted in Edmonton, but might not be considered for other regions and therefore other standards pay no attention to it.

The defects which are unique to one protocol and were not found in the other three standards are listed as follows:

- The PACP:
  - Lining Defects; this category is not defined by SRM or the early edition of COE.
  - Weld Failure; none of editions of the COE define this category.
  - Point Repair; same as weld failure, this category is not defined by the early edition of COE either.
  - Brickwork; the SRM4 has a separate section for brick sewers. However, none of the COE editions do not take this type of sewer system into account since it is not used in Edmonton.
- The SRM4:
  - Intruding Sealing Ring; is solely specified in the SRM4 and could not be found in any of the other three protocols.
  - Defective Repair; none of the editions of COE standard consider this category as a structural defect.
  - Weld Failure for Plastic and Steel; which like defective repair, the COE editions do not consider as a defect category.

- The COE Early Edition:
    - Sags; the PACP and the SRM4 do not consider sag as a structural defect. The reason for this matter is explained in the following section of this chapter.
- The COE Modified Edition:
    - Sags; the modified edition of the COE is the only protocol which has the category of sags in common with the COE early edition.
    - External Pipe; is when a pipe intrudes through the wall of a pipe. None of the other protocols defines this as a structural defect.

Sag or subsidence is resulted from the loss of soil under the pipes (NAAPI, 2003). This phenomenon is usually spotted at the joints. The early stages of sag development could be recognized through infiltration and gaps around the joints or service laterals.

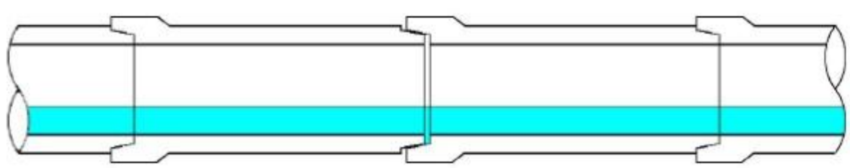

Figure 3.2.Early stage of sag, presence of gap at the middle joint (SRM, 2001)

With further infiltration, more soil is washed off from beneath the pipe and therefore the pipe will have less structural support and displaces more. This can result in displaced joints, open joints, and higher water level in the pipe.

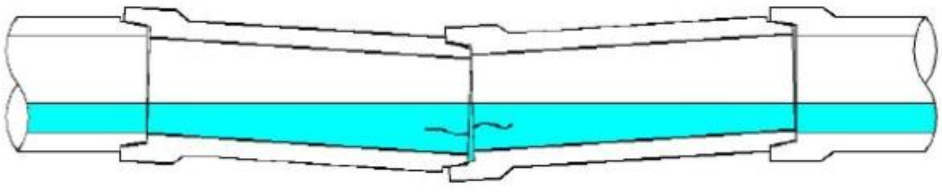

Figure 3.3. Moderate sag with displaced joint/open joints (SRM, 2001)

When sag develops to its ultimate stage, the presence of deformation and cracking is inspected. These defects are created due to severe joint displacements. In this case the camera can submerge and make further inspections impossible. The associated defects can be open and displaced joints, cracks, fractures, and deformations.

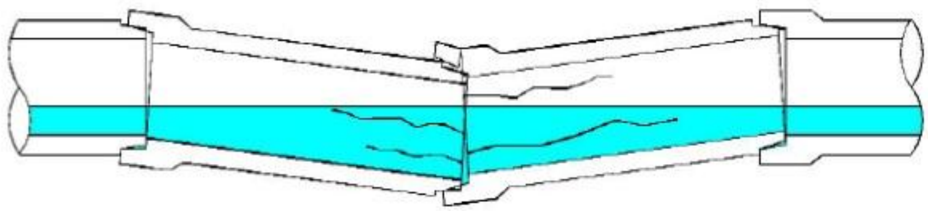

Figure 3.4.Deformations and fractures present at improved stages of sag (WRc 2001)

The SRM4 and the PACP do not consider sag as an explicit structural defect, since it results in the aforementioned structural defects. The more severe the sag is the more visible and severe those structural defects become, hence there is almost no need to include sag in the structural coding. However, both of the early and modified editions of the COE record sags as a separate structural defects. The presence of a severe sag in the pipe segment will result in rejecting the pipe segment by the early edition of COE. Although, the modified edition of COE grades the same pipe segment as “poor”, which is one stage before failure.

3.3 Qualitative Comparison of Structural Condition Grading Systems

In the Section 3.2, the coding system for different defects in a pipeline advised by the PACP, the SRM4, and both of the early and modified editions of the COE were compared to each other. The description of each code for recording the structural defects for each standard was reviewed. Using the PACP as the basis for the comparison, the equivalents of the PACP codes were found in the SRM4 and the COE's early and modified editions. This comparison illustrated each of the coding system's capabilities in reflecting the existing physical conditions of the inspected pipe segment.

In addition to the advantages of comparing the coding systems, it is important to understand how each protocol rates the recorded structural defect. The reason for this matter is that the defects affect the outcome of the pipeline segment's assessment relative to their importance in the protocols' structural grading systems. The protocols may consider different levels of effectiveness for a certain defect in the final structural condition grading results.

In this section, common defects are compared in terms of their significance in each protocol's structural condition grading system.

3.3.1 Defect Deduct Values

The PACP, the SRM4, the COE early edition and the COE modified edition assign different ranges of deduct values to the structural defects. Estimating on the values of the defects that are recorded for the inspected pipe segments, the condition grade of the pipe segment is established. Table 3.11 presents a comparison of the deduct value ranges for structural defects. Complete tables of structural deduct values for the PACP, the SRM4, and the COE's early and modified editions are provided in the appendices A to D.

Table 3.11. Ranges of the Deduct Values for All Defects from the Four Protocols

Protocol	**PACP**	**SRM4**	**COE Early Ed.**	**COE Modified Ed.**
Deduct Value Range	1 - 5	1 - 165	1 - 115	1 - 100

The maximum deduct value in each protocol corresponds to a collapsed pipe. An intact new pipe receives the minimum deduct value defined by each protocol.

The comparison of the deduct values for common structural defects are shown in Table 3.12.

Table 3.12. Comparison of Deduct Values for Common Structural Defects

<table>
<tr><th rowspan="2">Defects and Severity Level</th><th colspan="4">Deduct Values for Defects</th></tr>
<tr><th>PACP</th><th>SRM4</th><th>COE Early Ed.</th><th>COE Modified Ed.</th></tr>
<tr><td colspan="5">Cracks</td></tr>
<tr><td>Circumferential</td><td>1</td><td>10</td><td>1</td><td>10</td></tr>
<tr><td>Longitudinal</td><td>2</td><td>10</td><td>2</td><td>37</td></tr>
<tr><td>Spiral</td><td>2</td><td>40</td><td></td><td></td></tr>
<tr><td>Multiple</td><td>3</td><td>40</td><td>4</td><td>54</td></tr>
<tr><td colspan="5">Fractures</td></tr>
<tr><td>Circumferential</td><td>2</td><td>40</td><td>2</td><td>33</td></tr>
<tr><td>Longitudinal</td><td>3</td><td>40</td><td>4</td><td>68</td></tr>
<tr><td>Spiral</td><td>3</td><td>80</td><td></td><td></td></tr>
<tr><td>Multiple</td><td>4</td><td>80</td><td>5</td><td>84</td></tr>
<tr><td colspan="5">Broken</td></tr>
<tr><td>1 Clock Pos.</td><td>3</td><td rowspan="3">80</td><td rowspan="3">110</td><td rowspan="3">100</td></tr>
<tr><td>2 Clock Pos.</td><td>4</td></tr>
<tr><td>3 & more Clock Pos.</td><td>5</td></tr>
<tr><td colspan="5">Hole</td></tr>
<tr><td>1 Clock Pos.</td><td>3</td><td>80</td><td rowspan="3"></td><td>86</td></tr>
<tr><td>2 Clock Pos.</td><td>4</td><td rowspan="2">165</td><td rowspan="2">100</td></tr>
<tr><td>3 & more Clock Pos.</td><td>5</td></tr>
</table>

Table 3.12. Comparison of Deduct Values for Common Structural Defects, Cont'd

Defects and Severity Level	Deduct Values for Defects			
	PACP	**SRM4**	**COE Early Ed.**	**COE Modified Ed.**
Deformation				
< 5% Area Reduction	4	20	2	34
5%-10% Area Reduction		80	4	70
> 10% Area Reduction	5	165	100	91
Collapsed Pipe	5	165	115	100
Joint Displacement				
Light (up to 1.0 Pipe Wall Thickness)			2	28
Medium (to 1.5 Pipe Wall Thickness)	1	1	3	59
Large (> 1.5 Pipe Wall Thickness)	2	2	100	79
Soil Visible		80		
Open Joint				
Light (up to 1.0 Pipe Wall Thickness)			1	25
Medium (1.0 to1.5 Pipe Wall Thickness)	1	1	2	
Large (> 1.5 Pipe Wall Thickness)	2	2	5	72
Soil Visible		165		
Surface Damage				
Roughness Increased	1	5	1	28
Surface Spalling	2			
Aggregate Visible	3	20	2	59
Aggregate Projecting	3			
Aggregate Missing	4			
Reinforcement Visible	5	120	4	79
Reinforcement Corroded	5			
Missing Wall	5			

Table 3.12 shows that if the protocols do not consider a particular sub-defect category, the deductibles are not assigned to them either. For instance, the PACP and the SRM4 do not consider joint displacements smaller than 1.5 times the pipe wall thickness as a structural defect. Using Table 3.12, Figures 3.5, 3.6, and 3.7 are generated for the percentages of the defects' deductibles for different severity levels, relative to the maximum deduct value that each protocol defines. As the

defects become more severe, their deduct values become a larger percentage of the collapsed value. The structural defect severity levels are generally categorized as light, moderate, and severe. For instance, circumferential and longitudinal cracks are noted as light and moderate cracks respectively, whereas multiple cracks are noted as “severe”. Using this approach, relative percentage of the deduct values for each protocol per severity level can be compared. Figure 3.5 presents the deduct values’ relative percentage to the maximum deductibles established by all four protocols for light severity defects.

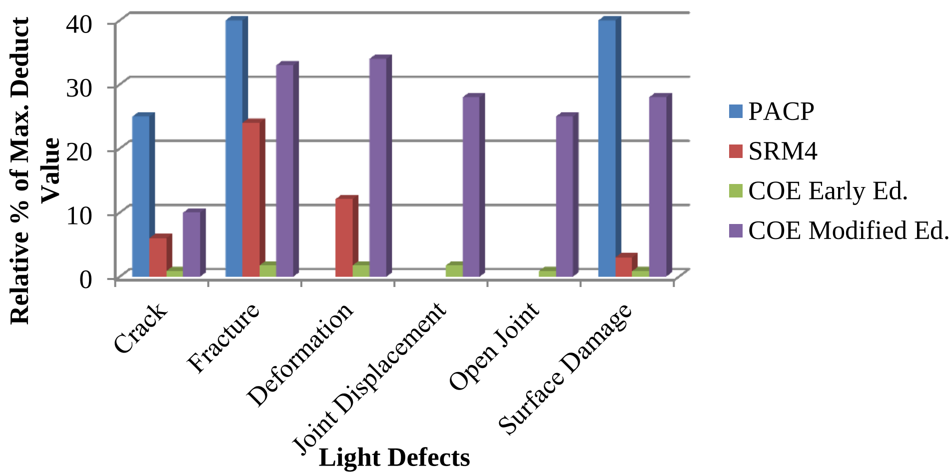

Figure 3.5. Comparison of Deduct Values for Light Structural Defects for the Protocols

Figure 3.5 indicates that the PACP and he SRM4 do not consider light displaced and open joints as structural defects. Also, the PACP does not include light deformations in its structural condition grading calculations either. The deductibles for the early edition of the COE are significantly low in comparison to the PACP, the SRM4, and the COE modified. The maximum deductible for the COE-early edition is 1.74% and corresponds to light fractures. The PACP assigns the highest deduct value to the light structural defects than all of the protocols, ranging from 25% for light cracks to 40% to light fractures and light surface damages. However, this does not necessarily result in higher structural grading results by the PACP. For example, in the case of inspecting a pipe segment with only one light fracture, both of the PACP and the early edition of the COE grade the pipe segment as “2” despite their noticeable difference in the deduct values they assign to this defect. This point is due to the different structural condition grading approaches that each of the protocols adopt. Final structural condition grading calculation methods by the four protocols are presented in Section 2.8.

Fracture appears to be the most important light structural defect for the condition assessment protocols except for the modified edition of COE, which assigns a slightly higher deduct value to light deformation. Figure 3.6 presents the relative percentage of maximum deduct values for moderate severity level defects for all four protocols.

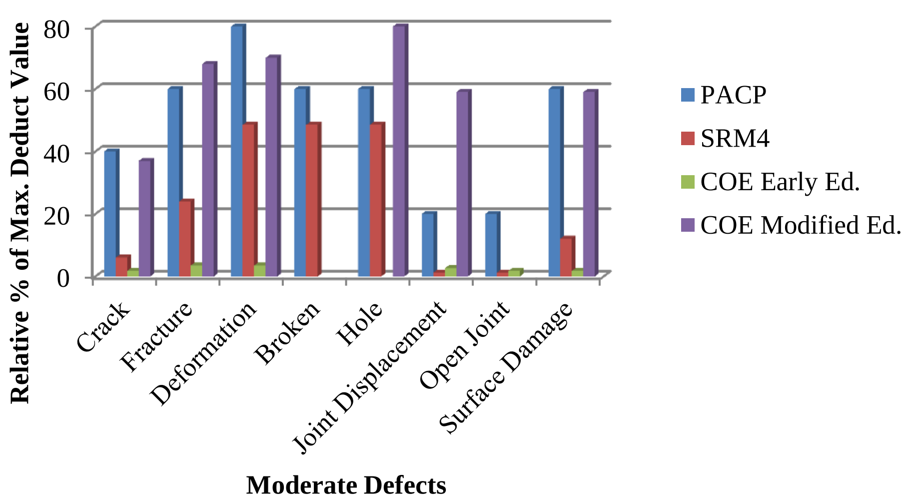

Figure 3.6. Comparison of Deduct Values for Moderate Structural Defects for All Four Protocols

The maximum deductible for the COE-early edition is 1.74% and corresponds to light fractures. None of the early and modified editions of the COE consider a moderate severity level for a broken pipe. Therefore a broken piece receives the maximum deduct values by the COE editions. The early edition of COE does consider “hole” as a separate structural category, and combines it with broken. Similar to light defects, the early edition of the COE assigns significantly low deduct values to the moderate defects when compared to the other three protocols. A maximum of 3.5% is assigned using this protocol to the most concerning moderate defects: moderate deformations and fractures. On the other hand, the PACP and the modified edition of the COE assign 80% of the maximum deduct values to the moderate deformations and holes respectively. However, using the early edition of the COE, the final structural condition grading result can be higher than the PACP, the SRM4, or the modified edition of COE. As an example, a pipe segment which is moderately fractured receives a structural grade of “3” from the PACP, the SRM4, and the modified edition of COE. The COE early edition grades the same pipe segment as “4”, which is only one level lower than failure. This matter is caused by how the structural condition grading thresholds are defined by the early edition of the COE. The protocols’ structural grading calculation methods and thresholds are presented in Section 2.8. Although the protocol’s deduct values range from 1 to 115, a defect with a deduct value of “4”, puts the pipe segment at a poor level which means a grade “4”. A more detailed comparison on the protocols’ approaches to compute the final structural condition grading of the inspected pipe segments is performed in the following section of this chapter.

It is also noticed in Figure 3.6 that all of the protocols with exception of the modified edition of the COE, assign the highest deduct value to moderate deformation. The modified edition of the COE considers hole to be more important than any other moderate structural defect.

Figure 3.7 presents the relative percentage of deduct values for sever structural defects for all of the four protocols.

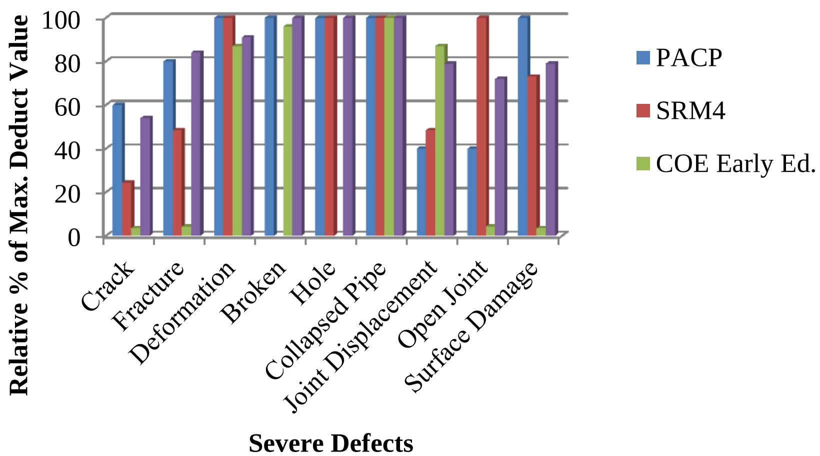

Figure 3.7. Comparison of Deduct Values for Severe Structural Defects for All Four Protocols

The category of collapsed pipe is noted in Figure 3.7, as all of the protocols consider this defect as a severe structural defect. Obviously all of the four protocols assign their highest deduct values to a collapsed pipe. Whereas crack is the category which receives the lowest deduct values by all four protocols. Similar to light and moderate defects, the early edition of the COE assigns low deduct values to some defects with respect to the PACP, the SRM4 and the modified edition of the COE's deduct values. This is observed for crack and surface damage with a relative percent deduct value of 3.5% and 4.3% for fracture and open joint. However, as it was explained for moderate defects, the early edition of the COE's final grading may even be higher than the other three protocols. The reason is explained in the following section of this chapter.

Also, from Figure 3.7 it is observed that the SRM4 pays noticeable attention to how severe pipe joints are detached from each other. The SRM4 assigns the highest deduct value than the other protocols to a severe open joint, when the soil is visible beyond the joint. Based on the SRM4's concept for open joints, when the joints are separated from each other to the level that the soil becomes visible beyond the joints, the pipe network does not exist anymore. Therefore the pipe network is not intact and the segment is rejected.

3.3.2 Structural Condition Grading Computation Approaches

In the previous section the deduct values for different defects at three severity levels of low, moderate and high from four different protocols were discussed. It was mentioned that if a protocol assigns a higher deduct value to a certain defect than the other protocol, it does not necessarily result in a worse condition grade for the inspected pipe segment. The reason for this, is how the protocols estimate the final structural condition grade based on the recorded defects and their deduct values.

Of the four protocols, the PACP assigns higher deduct values to defects. However, the PACP takes an average of the deduct values along the pipe segment to establish the final structural condition grading. For instance, assume that the structural defects in an inspected pipe segment include a deformed spot with less than 10% of the cross-sectional area (which receives a deduct value of "4" out of "5"). The same pipe also includes a spot with multiple cracks (which receive a deduct value of "2" out of "5"). The structural condition grading for this pipe segment according to the PACP is the average of 2 and 4and so is "3".

The SRM4 takes only the most severe structural defect into account for structural condition grading. It is stated in the SRM4 that a sewer pipe is in its weakest point's condition.

The early and modified editions of the COE use parameters such as the peak score, total score, and mean score of the inspected defects' deduct values for a pipe.

The modified edition of the COE considers a fourth parameter to take into account the effects of multiple defects for a pipe segment. Each of the parameters should be compared to pre-determined thresholds. The parameter which results in the highest grade through its comparison with the thresholds decides the final structural condition grade of the pipe segment.

It should be noted that according to the early edition of the COE, although the protocols' deduct values range from 1 to 115, the deduct value required to fail a pipe segment through peak score thresholds is 5[1]. This results in the rejection of the pipe segments due to the presence of defects such as severe fracture.

3.4 Summary

In this chapter sewer pipeline structural condition assessment protocols, the PACP, the SRM4, and both the early and modified editions of the COE were qualitatively compared. The first portion of this comparison centered on the protocols' coding systems, where the inspected structural defects in sewer pipes are described and recorded. It was noted that the PACP defines larger number of structural defects than the rest of the protocols. It was also noted that some protocols consider certain categories of defects which are not recognized as structural defects by one or two other protocols. For instance, both of the COE editions consider "sag" as a structural defect category, while the PACP and the SRM4 do not take it into account. Another example is "hole" which the early edition of COE do not define a separate category for, and the rest of the protocols consider it with different levels of severity. All of the defect categories exclusive to each of the four protocols were introduced in Section3.2.9.

The second portion of the comparison was conducted on the protocols' structural condition grading systems. Every protocol defines deduct values for different structural defects. These values for the same defect categories were compared among the four protocols. The relative percentages of the maximum deduct value

[1] Refer to Section 8 of Chapter 2 for the complete table of structural thresholds.

for different levels of defect's severity were presented and the observations were discussed in Section 3.3.1. Each protocol's structural condition grading approach was also considered with details.

Assigning different deduct values to certain structural defects, in addition to the each protocol's unique grading approach may result in different structural condition grades for the same pipe segment. These differences are better studied by implementing the four protocols in practical experiments, and the findings are presented and discussed in the following sections of the study.

Chapter 4: Quantitative Comparison of the Four Structural Condition Assessment Protocols Using 20 Pipe Segment Surveys

4.1 Introduction

The protocol used to inspect and assess sewer pipe segments should describe the actual physical condition of the pipe segment at the time of the survey. Therefore, since the existing defects in a pipe segment do not change by how they are recorded, different coding systems should result in the same description, and ultimately in the same structural condition grade.

In the previous chapter, sewer pipeline condition assessment protocols, the PACP, the SRM4, and both the early and modified editions of the COE were compared comprehensively from a qualitative perspective. The coding systems were studied and their differences in characterizing the inspected structural defects were pointed out. The protocols' condition grading systems were compared as well, and it was observed that their deduct value ranges and final condition grade computation methods are dissimilar. All of these differences may result in discrepancies between the structural condition grades which are computed by the each of the protocols.

In order to be able to study how different the structural condition grading results are, the protocols should be implemented in experiments. To do so, 20 pipe segment surveys form neighborhoods of Edmonton are selected, and reviewed by each of the four protocols in this chapter. The selected pipe surveys were recorded over two years, starting from 2010 with a total duration of approximately 170 minutes. Each survey was reviewed four times and the structural defects were coded using the PACP, the SRM4, and the COE editions. Survey reports were generated separately based on each of the four protocols.

Having completed reviewing the surveys, deduct values defined by each of the protocols were assigned to the recorded defects. Structural condition grades of the pipe segments were computed by the PACP, the SRM4, the COE early edition and its modified edition. One example of this process is presented in this chapter, and the complete details of the survey reviews and their structural grading calculations can be found in Appendix E.

The assessment results are compared and the observed facts about the comparison are presented and discussed.

4.2 Test Sample Characteristics

The 20 selected sewer pipe surveys are selected from the neighborhoods' sewer network in Edmonton. None of the selected surveys include records for time earlier than 2010. Special care was taken when selecting the pipe segments' surveys. In doing so, the following criteria were taken into consideration:

1. Sewer System Type: to represent sanitary, storm, and combined sewer systems, six pipe segments were selected for each system. Two segment from sanitary and storm systems are reviewed twice with different inspection dates and are treated as separate pipe segments.
2. Pipe Size: since the selected surveys are from urban neighborhoods, typical sewer pipe sizes for such areas are considered in the study. The pipe size in

the study ranges from 200 to 375 millimeters and smaller and larger pipe sizes are not used for the experiment.

Table 4.1 summarizes the physical properties of the pipe segments selected for the experiment.

Table 4.1. Physical Properties of the 20 Selected Sewer Pipe Segments

Sanitary			Storm			Combined		
Pipe Size (mm)	**Pipe Material**	**Pipe Length (m)**	**Pipe Size (mm)**	**Pipe Material**	**Pipe Length (m)**	**Pipe Size (mm)**	**Pipe Material**	**Pipe Length (m)**
200	Vitrified Clay Tile	33.20	200	Clay Tile	40.00	200	Clay Tile	65.75
200	Concrete	36.23	200	Clay Tile	109.70	200	Reinforced Concrete	113.04
200	Concrete	49.30	200	Clay Tile	109.70	250	Concrete	30.00
250	Clay Tile	90.60	250	Concrete	37.68	250	Clay Tile	57.62
250	Clay Tile	90.60	250	Concrete	40.00	300	Clay Tile	107.26
300	Concrete	39.00	300	Concrete	75.00	375	Concrete	74.37
375	Clay Tile	73.30	375	Reinforced Concrete	89.95			
Total Length		412.23	**Total Length**		502.03	**Total Length**		448.04

4.3 Coding and Structural Condition Grading, Using the Four Protocols for One Example Pipe

In this section, the survey inspection results for one of the pipe segments are presented as an example. The pipe segment is coded separately for structural defects using the PACP, the SRM4 and both of the early and modified editions of the COE. The pipe segment's condition is then structurally graded following each of the four protocols. The selected pipe segment for this section is a 200-millimeter combined-sewer pipe with 65.75 meters of length.

Table 4.2 shows the sample structural defects which are coded based on the PACP's coding system. The first two columns of the table provide information regarding the location of the defect in the pipe segment. The column "Defect Count" is calculated using the length of the defect. Since the PACP considers the units of the defect occurrence instead of the defect length in the structural grading calculation, any length smaller than one meter is counted as one unit of occurrence. Defect count for the defects with no length is “1”.

Table 4.2. Sample Defect Coding and Deduct Values by the PACP

Dist	Dist_to	Defect Count	Code	Description	Deduct Value
1.5		1	JOM	Joint Offset Medium	1
16.5	17.0	1	FS	Spiral Fracture	3
17.2	17.8	1	D	Deformed	4
17.2	18.3	2	FL	Longitudinal Fracture	3
18.5	20.2	2	FL	Longitudinal Fracture	3
26.8	28.0	2	FL	Longitudinal Fracture	3
27.8	30.0	3	SRIC	Chemical Surface Damage, Roughness Increased	1
31.8	32.2	1	D	Deformed (< 10%)[1]	4
32.4	34.0	2	FL	Longitudinal Fracture	3
35.7	36.2	1	FM	Multiple Fracture	4
40.4	41.0	1	FC	Circumferential Fracture	2
47.7	50.0	3	FL	Longitudinal Fracture	3
61.7	62.2	1	FS	Spiral Fracture	3
62.5	64.0	2	FL	Longitudinal Fracture	4
62.5		1	JOM	Joint Offset Medium	1
62.5	63.0	1	D	Deformed (<10%)	4
65.5	65.75	1	SRIC	Chemical Surface Damage, Roughness Increased	1

Using the defect codes and their deduct values which the PACP assigns to each code, the structural condition grade of the pipe segment can be estimated as count of defects at a certain deduct value × deduct value:

- Segment Grade “1” Score: 6 × 1= 6
- Segment Grade “2” Score: 2
- Segment Grade “3” Score: 39

[1] Less than 10% reduction in the cross-sectional area

- Segment Grade "4" Score: 24
- Structural Pipe Rating (Sum of all of the segment grade scores): 71
- Structural Pipe Rating Index (Structural Pipe Rating divided by sum of defect counts): 2.73 ≈ 3

Based on the PACP, this pipe segment receives a structural condition grade of "3", implying that the pipe is in fair structural conditions.

Table 4.3 shows the structural defects coded based on the PACP's coding system for the same pipe segment. Since the SRM4 only considers the maximum deduct value that the defects receive, "defect count" is not included in this table. The SRM4 denotes the deduct values by "Unit Score", as shown in the Table 4.3. The structural condition grading by the SRM4 is estimated by comparing the maximum deduct value of the pipe segment's defects to the SRM4 structural grading thresholds which were presented previously in Section 8.2 in Chapter 2.

Table 4.3. Sample Defect Coding and Deduct Values by the SRM4

Dist	Dist_to	Code	Description	Unit Score
1.5		JDL	Joint Displaced Large	2
16.5	17.0	FS	Fracture Spiral	80
17.2	17.8	D (0-5%)	Deformed	20
17.2	18.3	FL	Fracture Longitudinal	40
18.5	20.2	FL	Fracture Longitudinal	40
26.8	28.0	FL	Fracture Longitudinal	40
27.8	30.0	SWS	Surface Wear Slight	5
31.8	32.2	D (5-10%)	Deformed	80
32.4	34.0	FL	Fracture Longitudinal	40
35.7	36.2	FM	Fracture Multiple	80
40.4	41.0	FC	Fracture Circumferential	40
47.7	50.0	FL	Fracture Longitudinal	40
61.7	62.2	FS	Fracture Spiral	80
62.5	64.0	FL	Fracture Longitudinal	40
62.5		JDL	Joint Displaced Large	2
62.5	63.0	D (0-5%)	Deformed	20
65.5	65.75	SWS	Surface Wear Slight	5

The recorded peak score for this pipe segment is 80. Therefore, the SRM4 grades this pipe segment with a structural condition grade of “4” based on its structural grading thresholds, implying that the pipe is in poor structural conditions.

Table 4.4 shows the structural defects for the same pipe segment coded based on the COE early edition’s coding system. The column “defect count” in this table is the length of the pipe infected by the defect. This column’s value is “1” for the defects which length is not recorded for them. The deduct value which each of the defects receive is shown under the “unit score” column. The deduct value multiplied by the defect count is the score which each defect receives for its length of occurrence. The important difference between Table 4.4 and Tables 4.3 and 4.2 which are generated based on the SRM4 and the PACP, respectively is that the presence of sag is recorded as a structural defect, as the COE early edition defines a separate structural defect category for sags.

Table 4.4. Sample Defect Coding and Deduct Values by the COE Early Edition

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5		1.0	JM	Joint Displaced Moderate	3	3.0
16.5	17.0	0.5	FM	Fracture Moderate	4	2.0
17	18.0	1.0	SM	Sag Moderate	2	2.0
17.2	17.8	0.6	DM	Deformed Moderate	4	2.4
17.2	18.3	1.1	FM	Fracture Moderate	4	4.4
18.5	20.2	1.7	FM	Fracture Moderate	4	6.8
26.8	28.0	1.2	FM	Fracture Moderate	4	4.8
27.8	30.0	2.2	HL	Surface Damage Light	1	2.2
31.5	32.6	1.1	SM	Sag Moderate	2	2.2
31.8	32.2	0.4	DM	Deformed Moderate	4	1.6
32.4	34.0	1.6	FM	Fracture Moderate	4	6.4
35.7	36.2	0.5	FS	Fracture Severe	5	2.5
40.4	41.0	0.6	FL	Fracture Light	2	1.2
47.7	50.0	2.3	FM	Fracture Moderate	4	9.2
61.5	63.0	1.5	SM	Sag Moderate	2	3.0
61.7	62.2	0.5	FM	Fracture Moderate	4	2.0
62.5	64.0	1.5	FM	Fracture Moderate	4	6.0
62.5		1.0	JM	Joint Displaced Moderate	3	3.0

Table 4.4. Sample Defect Coding and Deduct Values by the COE Early Edition, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
62.5	63.0	0.5	DM	Deformed Moderate	4	2.0
65.5	65.8	0.3	HL	Surface Damage Light	1	0.3

The parameters for structural condition grade calculation, peak, total, and mean scores for this pipe segment are calculated as below. The formulas for calculating peak, total, and mean scores by the early edition of COE are presented in Section 8.3 in Chapter 2, along with its structural grading thresholds.

- Peak Score: 5
- Total Score: 67.0
- Mean Score: 0.98

The greatest grade produced by comparing the three parameters to the structural grading thresholds is 5 and is decided by peak score. Therefore, the early edition of COE assigns a structural grade of "5" to this pipe segment, which means that the pipe has structurally failed and requires urgent attention.

Table 4.5 shows the structural defects coded based on the COE modified edition's coding system. The column definitions are similar to table 4.4 for the COE early edition defect coding.

Table 4.5. Sample Defect Coding and Deduct Values by the COE Modified Edition

Dist	Dist_to	Defect Count	Code	Description	Unit Weight	Defect Weight
1.5		1	JM	Moderate Displaced Joint	62	62
16.5	17	0.5	FM	Moderate Fracture	68	34
17	18	1	SL	Light Sag	25	25
17.2	17.8	0.6	DM	Moderate Deformation	70	42
17.2	18.3	1.1	FM	Moderate Fracture	68	74.8

Table 4.5.Sample Defect Coding and Deduct Values by the COE Modified Edition, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Weight	Defect Weight
18.5	20.2	1.7	FM	Moderate Fracture	68	115.6
26.8	28.0	1.2	FM	Moderate Fracture	68	81.6
27.8	30.0	2.2	HL	Light Surface Damage	21	46.2
31.5	32.6	1.1	SL	Light Sag	25	27.5
31.8	32.2	0.4	DM	Moderate Deformation	70	28.0
32.4	34.0	1.6	FM	Moderate Fracture	68	108.8
35.7	36.2	0.5	FS	Severe Fracture	85	42.5
40.4	41.0	0.6	FL	Light Fracture	33	19.8
47.7	50.0	2.3	FM	Moderate Fracture	68	156.4
61.5	63.0	1.5	SL	Light Sag	25	37.5
61.7	62.2	0.5	FM	Moderate Fracture	68	34.0
62.5	64.0	1.5	FM	Moderate Fracture	68	102.0
62.5		1.0	JM	Moderate Displaced Joint	62	62.0
62.5	63.0	0.5	DM	Moderate Deformation	70	35.0
65.5	65.8	0.3	HL	Light Surface Damage	21	6.3

Similar to the COE early edition, peak, total, and mean scores should be calculated for the COE modified edition's structural grading as well. In addition to these three parameters, the defects should also be examined for multiple defect effect. The formulas for calculating peak, total, and mean scores by the early edition of COE are presented in Section 8.4 in Chapter 2, along with its structural grading thresholds. The four parameters are calculated as below:

- Peak Score: 85
- Total Score: 1141
- Mean Score: 17.35

- Multiple defect effect: Since none of the defects have repeated more than the required percentages specified in Table 2.4, the multiple defect effect does not apply in this case.

Comparing the peak, total, and mean scores to the COE modified edition's structural grading thresholds, the peak score thresholds indicate that the pipe segment receives a score of "4". This means that the pipe segment is in poor structural conditions based on the COE modified edition.

4.4 Coding and Structural Condition Grading, Using the Four Protocols for All Twenty Pipes

The same procedure described in the previous section was followed for all the other 19 pipe segments. The selected pipe surveys were reviewed, coded, and graded following the PACP, the SRM4, and both early and modified editions of the COE. A wide range of structural defect categories with different severities were inspected including cracks, fractures, broken pipes, holes, collapsed pipes, deformations, surface damages, and displaced and open joints. Also, some instances of sags were recorded based on both of the COE editions' coding requirements. No instances of lining defects, defective point repairs, weld failures, intruding sealing rings, or external objects were inspected. Number of recorded defects per category for each coding system for all of the 20 pipes is illustrated in Figure 4.1.

For the major categories which all of the four standards have in common, cracks, fractures, deformations, collapsed, displaced and open joints, and surface damages all of the protocols record the same number of defect occurrence. However, even in these common categories there exist some uncommon sub-categories. Both editions of the City of Edmonton do not record spiral cracks or fractures and code them as either circumferential or longitudinal defects. Also, since the early edition of the COE does not define "hole" as a defect category, it just codes holes as "broken pipes". Therefore the number of this category for the old edition of the COE differs than the rest of the coding systems. As stated in section 2.9 of chapter 3, none of the standards other than the COE editions consider sag as a structural defect category. Hence no records could be found for sags by the PACP or the SRM4.

Fractures and cracks have the most and the second most number of occurrence respectively, and surface damages are the third most occurring defects. Collapsed pipe has occurred only once to make it the least occurring structural defect in the 20 reviewed surveys. Also, two instances of broken pipes have been inspected.

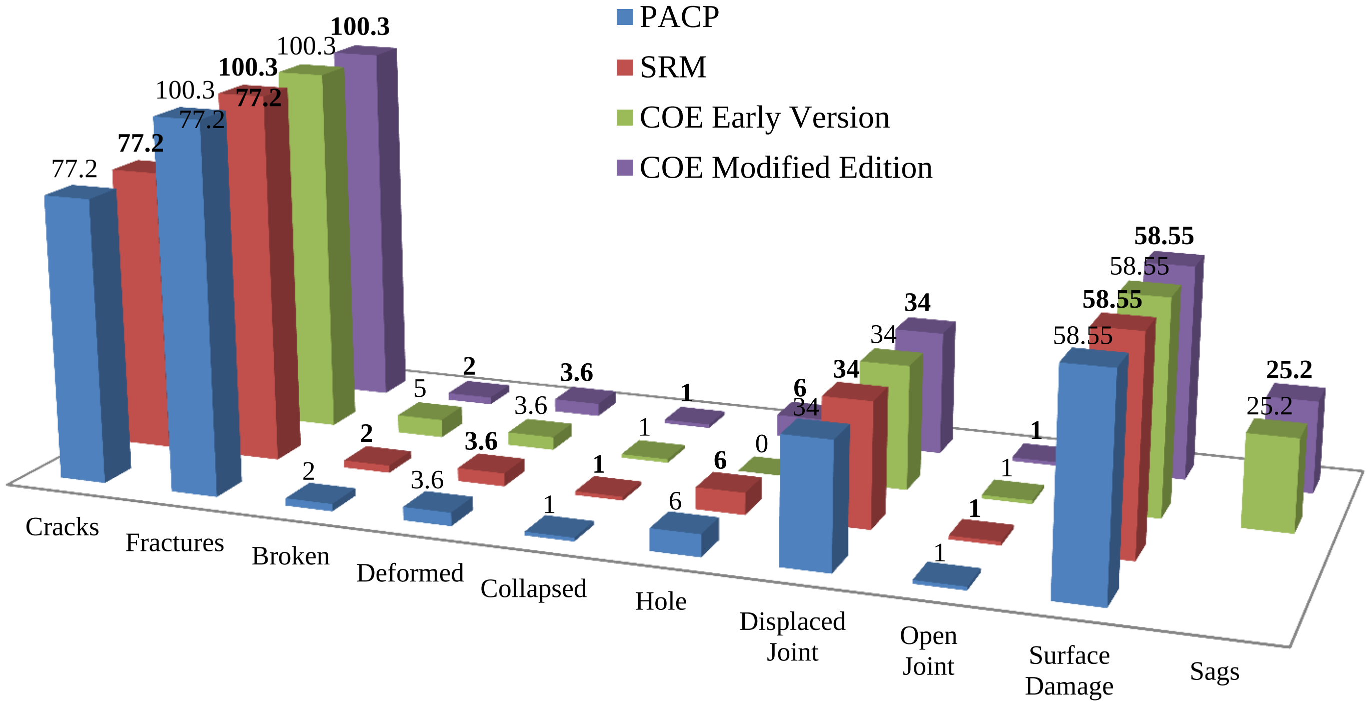

Figure 4.1. Counts of defect categories per each protocol coding system

Having completed the defect coding for all the 20 pipe segment surveys, the structural condition grades based on the PACP, the SRM4, and both of early and modified the COE are computed for the pipe segments. Table 4.6 illustrates the grading results for each of the pipe segments.

Table 4.6. Summary of the sample pipe segment survey reviews and grading results

Pipe Segment Number	**Sewer System**	**Pipe Size (mm)**	**Pipe Material**	**Length (m)**	**PACP**	**SRM4**	**COE Early Edition**	**COE Modified Edition**
1	Storm	375	Reinforced Concrete	89.95	3	4	4	4
2	Combined	200	Reinforced Concrete	113.04	2	4	5	4
3	Combined	200	Clay Tile	65.75	3	4	5	4
4	Storm	250	Concrete	37.68	4	5	5	5
5	Combined	300	Clay Tile	107.26	3	4	5	4
6	Combined	250	Clay Tile	57.62	3	4	5	4
7	Combined	375	Concrete	74.37	2	3	4	4
8	Storm	300	Concrete	75	2	3	4	4
9	Storm	200	Clay Tile	109.7	1	2	3	3
10	Storm	200	Clay Tile	109.7	1	5	5	5
11	Storm	200	Clay Tile	40	5	4	5	5
12	Sanitary	250	Clay Tile	90.6	3	4	5	5
13	Sanitary	250	Clay Tile	90.6	3	5	5	5
14	Sanitary	375	Clay Tile	73.3	3	5	5	5
15	Storm	250	Concrete	40	2	5	5	4
16	Sanitary	200	Vitrified Clay Tile	33.2	2	4	2	2
17	Sanitary	200	Concrete	49.3	2	4	4	3
18	Sanitary	300	Concrete	39	3	2	3	4
19	Sanitary	200	Concrete	36.23	2	2	2	4
20	Combined	250	Concrete	30	3	2	2	5

According to Table 4.6, not one single pipe segment is graded the same using the four protocols. Even though the number of uncommon defects inspected is not large, a noticeable diversity exists between the grading results. There exist cases where the grading results have more than two levels of difference. For instance, the PACP grades the pipe segment number 10 to be in excellent conditions. Whereas, the SRM4, and both the early and modified editions of the COE reject the pipe segment and assign a grade of five to it. The PACP assigns the deduct values ranging from 1 to 5 to the structural defects and computes the final grade by averaging the deduct values over the entire segment. In the pipe segment number 10, 13 defects with a deduct value of "1" are inspected and one grade "5" defect which is a hole where soil could be seen beyond it. Performing the averaging operation on the deduct values assigned to the defects, the final grade will be close to "1". The SRM5 on the other hand, fails the pipe segment due to the presence of the hole with the maximum deduct value assigned to it. The defined thresholds for peak score in the COE editions also result in rejection of this pipe segment due to the presence of the hole, although the early edition of the protocol defines the defect as "broken pipe".

Another instance where one of the protocols, the SRM4 in this case, grades the pipe segment very differently than the rest of the protocols is pipe segment number 16. The PACP and both early and modified editions of the COE resulted in a grade of "2" in their final structural condition grade computations. The SRM4 grades this pipe segment "4". The major frequent inspected structural defects in this pipe segment are cracks and fractures, the most severe of which are spiral fractures. The PACP assigns deduct values from 1 to 3 to the inspected structural defects of this pipe segment and its averaging method of condition grade calculation results in a grade of "2". The COE early and modified editions, not having defined sub-categories for spiral fractures and considering them as light fractures in this particular case, both grade this pipe segment with “2”. The SRM4, distinguishes the spiral fractures from circumferential and longitudinal fractures and assigns a higher deduct values to them, 80 out of 165. The comparison of this deduct value with the SRM4’s structural thresholds will result in labeling the pipe segment with poor structural conditions, a grade of “4”.

Another approach to consider the differences in the structural grading results from the PACP, the SRM4 and the COE editions, is to compare the frequency of occurrence of different grades by each protocol. Figure 4.2 is generated using Table 4.6 and shows the frequency of structural grades computed by each protocol.

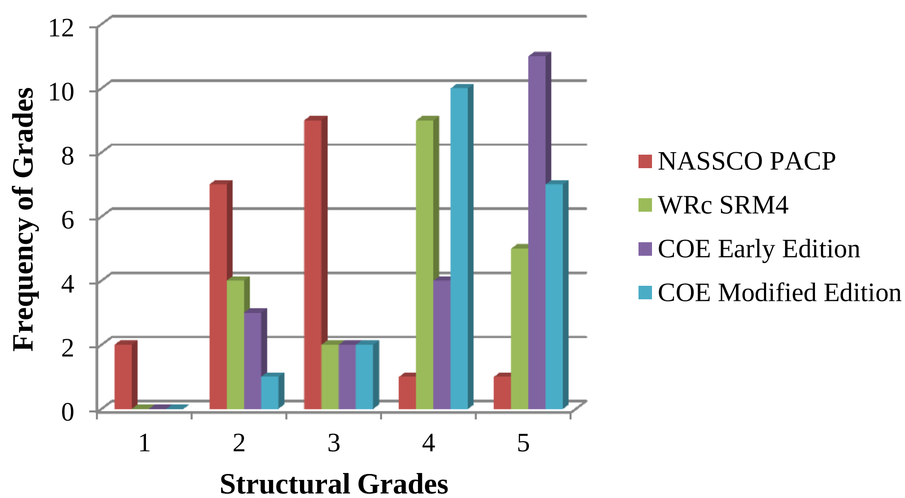

Figure 4.2. Frequency of Structural Grades for each Protocol

According to Figure 4.2., it is the PACP grades the pipe segments at lower grades than the SRM4 and both the early and modified editions of the COE. Ninety percent of the pipe segments received grades form one to three when using the PACP while only 30% of the pipe segments are graded in that range when using the SRM4. The early editions of the COE grade 25% of the pipe segments with the first three structural grades. This number for the modified edition of the COE is 15%. None of the pipe segments are in excellent structural conditions based on the SRM4 and the COE editions.

The early edition of the City of Edmonton's protocol has the highest number of pipe segments at Grade 5. Fifty-five percent of the pipe segments considered are rejected by this protocol. The SRM4 rejects 25% of the pipe segments, while this percentage for the modified edition of COE and the PACP is 35% and 5%, respectively.

4.5 Summary

The PACP, the SRM4, the COE early edition, and the COE modified edition each have their exclusive approach to recording and coding structural defects, assigning deduct values to them, and computing the final structural condition grade. These differences may result in dissimilar structural grading results by each protocol for the same sewer pipe segments. In order to study these differences and their causing factors, the protocols should be implemented in real experiments.

In this chapter, 20 sewer pipe surveys from Edmonton neighborhoods were selected and reviewed by each of the PAPC, the SRM4 and the COE editions separately. A noticeable discrepancy existed in the structural grading results by the four condition assessment protocols. The following observations were pointed out by studying the codes which each of the protocols label the inspected structural defects with and the pipe segments' final structural condition grading results:

- The protocols use different deduct values for the same structural defects which this point ultimately may result in dissimilar structural condition grades for the same pipe segments.
- There are certain codes in each of the protocols which do not exist in the rest of them. Encountering such defects in the surveys would influence the final structural condition grading results. An example for this point is "sag" which is considered a structural defect category by COE early and modified editions and not by the PACP and the SRM4.
- One important reason for dissimilar structural grading results by the protocols is their grade computation approach. The PACP uses an averaging method to assign the final structural grade to the considered pipe segment. The SRM4 grades the entire pipe segment based on its worst existing defect. Both of the COE editions compare parameters which are calculated based on the defects' deduct values, such as peak, total and mean scores, with pre-defined structural grading thresholds. The final structural condition grade of the pipe segment is the greatest grade resulted from these thresholds.
- The PACP structural condition grading results are relatively lower than the rest of the protocols. While the COE early editions has the highest rate of rejecting the pipe segments with 55%, the COE modified edition assigns

higher structural grades to the pipe segments than the other three protocols with 85% of the pipe segments receiving grades of “4” and “5”.

Chapter 5: Implementation of the Four Condition Assessment Protocols in a Sewer CCTV Database, Using the Structured Query Language (SQL)

5.1 Introduction

In Chapter 3, the four structural condition assessment protocols for sewer pipelines, the PACP, the SRM4, and the COE early and modified editions were qualitatively compared. Their differences in various areas such as defect coding, defect deduct values, and structural condition grade computations were presented and discussed.

It was stated in Chapter 4, that to comprehensively understand the existing discrepancies between the protocols, they should be implemented in real-world experiments. To do so, 20 sewer pipe inspection surveys from various neighborhoods of Edmonton were selected, reviewed, coded and graded following each of the four protocols. The structural condition assessment results by the PACP, the SRM4, and the COE editions were presented and the factors which caused the differences in the results were analyzed.

This chapter focuses on the conformity of the findings from the previous chapter's experiment, to the results obtained from an experiment with a much larger test sample. With the number of selected pipe segments for Chapter 4's experiment, the general trends in the structural grading for the four protocols were understood. However, the observations should be examined and verified using a larger sample of pipe segments.

To do so, a database of the CCTV survey reviews for more than 20,000 aged sewer pipe segments is assessed following each of the PACP, the SRM4, and the COE early and modified editions. The characteristics and properties of the database are fully discussed in Section 5.2 and the data preparation process is described in full details in Section 5.3. To implement each of the condition assessment protocols in the database, a relational database management system (RDBMS) is developed, using the structured query language (SQL) in Microsoft Access 2010 medium. The key capability of the RDBMS is to convert the protocols' coding systems to one another. For instance, if the original coding of the structural defects is conducted based on the COE early edition's coding system, the designed RDBMS re-generates the structural codes based on the PACP, the SRM4, and the COE modified edition. The development process and features of the RDBMS are also demonstrated in this chapter.

Using the designed RDBMS, the protocols' structural grading results are then compared pairwise to each other in order to comprehensively study the protocols' similarities and differences. The findings which were stated in chapter 4 are also examined with the results of these pairwise sets of comparisons.

5.2 Database Description

The sewer pipeline CCTV inspection database used for this section of the study includes 44,490 inspection surveys of 33,421 sewer pipe segments from various neighborhoods in Edmonton. The number defects is 657,391 recorded in those inspections over approximately 10 years including 131,465 structural defects and

99,154 non-structural defect records. The defects are all coded based on the early edition of the COE condition assessment protocol. The information recorded in each inspection survey consists of the physical properties of the pipe segment such as pipe diameter, total pipe length, sewer system type, and pipe material.

5.3 Data Preparation

Prior to implementing the PACP, the SRM4, and the COE early and modified editions for the database the following data records were eliminated from the database:

1. The pipe segments with “zero” pipe lengths and “zero” pipe sizes,
2. The defects with start distances exceeding the total pipe length,
3. The defects with negative lengths,
4. The defects which are counted based on their occurrence, such as joint related defects that had a recorded distance. There are cases which a noticeable portion of the pipe length is infected with such kinds of defects, and the length of the infected portion is recorded. In these cases, the number of the defect occurrence is calculated and taken into consideration.

5.4 The RDBMS Development Process

It was stated In Section 5.2 that the number of inspection surveys is greater than the number of pipe segments. This means multiple inspection surveys are available for some pipe segments. Therefore, a procedure is required for a consistent selection of the surveys. This is the main reason for developing the

RDBMS, since it implements the survey selection criteria on the database. The criteria for selecting the applicable data records for the study are:

- Inspection records with no structural defects are not required, and should not be used for the analysis. The reason for this matter is that non-structural defects do not affect the final structural grading results of the pipe segment.
- For the pipe segments with multiple inspection survey records, the survey with the earliest inspection date is selected. Usually the earliest inspections have more ties for worst condition states as no rehabilitative or operational maintenance actions had been taken on the pipe segment compared with its later date inspections. The selected data is presented in Section 5.5.

The RDBMS is the tool used to implement the PACP, the SRM4, and the COE early and modified editions for the sewer pipes CCTV database. The first step of this implementation consists of pipe segments' defect coding based on the four protocols' defect coding systems. Since the database defects are originally coded based on the COE early edition, the RDBMS should re-generate the structural defect codes by each of the other three protocols. Hence, the equivalents of the original defect codes, in the PACP, the SRM4, and the COE modified edition should be entered to the RDBMS. In doing so, the results of the qualitative comparison between the coding systems which was conducted in Chapter 3 are used. However it should be noted that some of the defect codes defined by the PACP, the SRM4, or the COE modified edition do not exist in the COE early edition defect coding system. Holes, lining defects, and point repairs, intruding services, and external pipes are all instances of structural defect categories which are not defined by the COE early edition but exist in the rest of the coding systems[4]. On the other hand, the COE early edition's sag could not be found in the PACP or the SRM4. To prevent this matter from affecting the study, it is assumed that the defect categories defined by the other protocols which do not exists in the COE's early edition have not occurred in the considered CCTV database. Also, the COE's sags will not affect the results, since the PACP and the SRM4 do not recognize them as structural defects and hence no deductibles are assigned to them.

To develop the RDBMS's defect code conversion feature, it was assumed that none of the defect categories which are not defined by the COE early edition have occurred in the sewer pipes CCTV inspection database. Also, the COE's sags are not noted as structural defects once defects are re-generated based on the PACP and the SRM4's coding systems.

The second step of implementing the four protocols in the database is structural condition grading, which is another functionality of the designed RDBMS. The deduct values advised by the PACP, the SRM4 and the COE early and modified editions for the structural defects are introduced to the RDBMS. The structural grading thresholds which the SRM4 and the COE editions use to compute the structural condition grade of the pipe segments are entered as well. Figure 5.1 is a

[4] Structural defect categories which are not in common between the protocols are introduced in section 2.9 of chapter 3.

snapshot of the COE early edition and the SRM4's structural grading thresholds input tables in the RDBMS. Computation of the pipe segments' structural grades by each of the four protocols is done within the RDBMS, by queries which are developed by structured query language. For the PACP, the structural condition grade is calculated by averaging the deduct values within a pipe segment. For the SRM4, the maximum deduct value assigned to the pipe segment's defects is compared with the SRM4's structural grading thresholds. For both of the COE early and modified editions, peak, total, and mean score parameters are calculated first and then are compared to the structural grading thresholds which are introduced to the RDBMS.

COEWeightRatingMap

Total	Mean	Peak	Rating
100	0.5	1	1
149	0.99	2	2
199	1.49	3	3
249	2.49	4	4
9999	999	999	5

SRM4WeightMap

Peak	Rating
9	1
39	2
79	3
164	4
999	5

Figure 5.1. Structural Threshold Tables for the COE early edition and the SRM4

One of the other important capabilities of the RDBMS is comparing the grading results produced by different protocols for identical pipe segments. Using the comparison outcomes, a comprehensive analysis on each of the protocol's approach is conducted and the results are discussed in Section 5.6 of this chapter.

5.5 Data Presentation

Having prepared and selected the applicable data pieces within the developed RDBMS, 14968 pipe segments meet the selection criteria with 97116 structural defects recorded over 1121.69 kilometers of length. The total number of the defects which the length is not considered for them (for example, joint defects), or the total length of the defects that their length is recorded, defines a parameter entitled "defect count". The sum of defect count for the applicable data used in the RDBMS reaches to 107770.9. The pipe segment diameters vary from 100 millimeters to 6250 millimeters, with approximately 90% of the pipe segments ranging from 200 to 450 millimeter diameters.

The number of inspected defects in the surveys is shown by defect count percentage per category of the defect in figure 4.5. Since the original database is coded by the COE early edition, sags are considered as structural defects. The second greatest defect count by approximately 30% of the entire structural defects belongs to sags, after cracks which have the 31% of the total defect counts. Collapsed pipe category, with very small number of occurrence is the least happening defect in the entire database with only 0.03% of defect counts. Percentages of different defect counts per category are illustrated in figure 5.2.

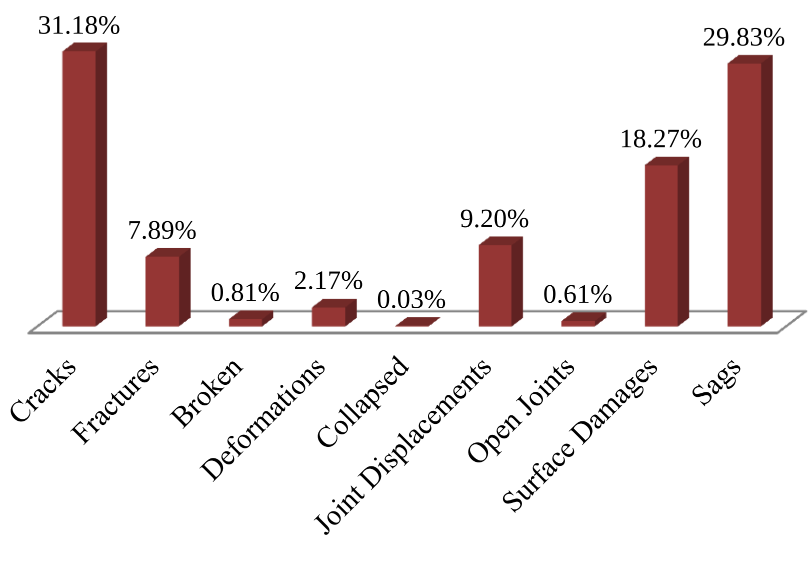

Figure 5.2. Percentages of Defect Counts per Category of Structural Defects

The inspected defects from the selected pipe segments which were manually reviewed in Chapter 4 comply with this database's defect distribution with only two exceptions. In the CCTV database, fractures stand ahead of cracks in count unlike the experiment in Chapter 4, and surface damages have a greater count than sags as well. However, fractures, cracks, surface damages, and sags together are the most occurring structural defects in chapter4's experiment and in complete compliance with the four most occurring structural defects in the CCTV database.

5.6 Structural Grading Results by the Four Protocols

Using the RDBMS, the PACP, the SRM4, and the COE early and modified editions are all implemented in the database separately and the grading results are presented in this section. Figure 5.3 illustrates the structural grading results.

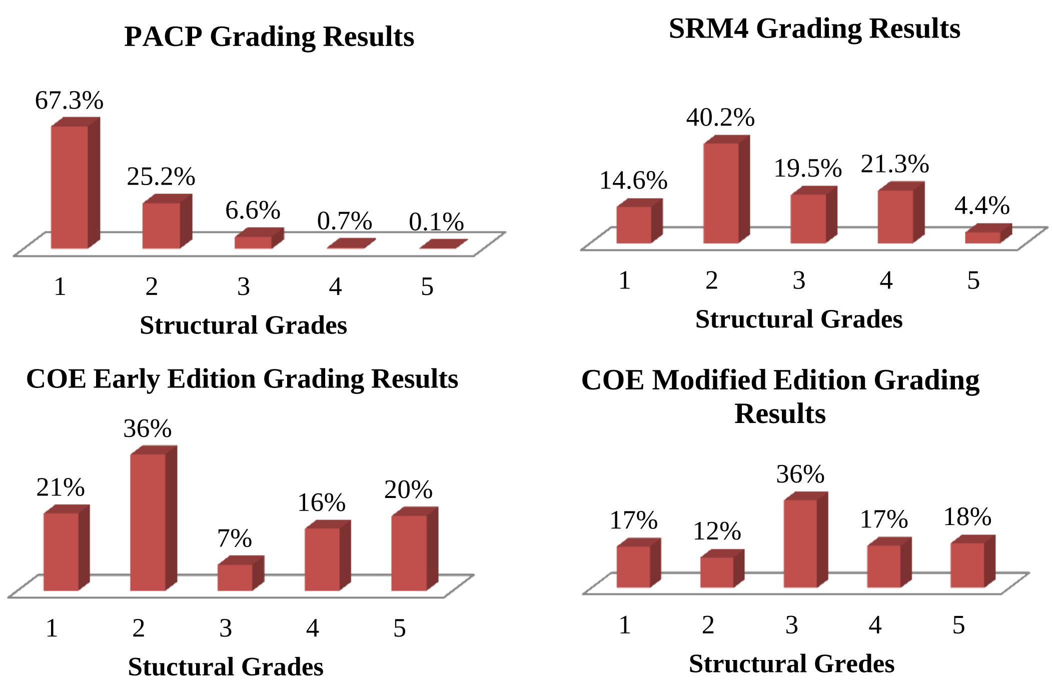

Figure 5.3. Structural Grading Results by the Four Protocols

The results generated using the four protocols show significant discrepancy among the protocols. The PACP results follow a falling trend as moving towards the higher grades. Sixty seven percent of the entire pipe segments are in excellent condition based on the PACP, with only 0.8% of the pipe segments graded “4” or “5”, which require urgent rehabilitative attention.

The SRM4 grades approximately 60% of the records at two or three, implying that a noticeable portion of the database is in either good or fair conditions.

The early and modified editions of the COE have the closest trends to each other among the four protocols. However, based on the modified edition the first three grades have started moving towards the critical grades of “4” and “5”, with 36% of the pipe segments receiving a grade of 3, and 29% graded at one or two. Whereas the early edition of the COE assigns only 7% of the pipe segments with grade 3, and 57% of the pipe segments is graded “1” or “2”.

5.7 Comparison of the findings for Structural Grading of 20 Pipe Surveys with the RDBMS’s Grading Results Using All Four Protocols

In Chapter 4, 20 sewer pipe segment inspection surveys were selected for implementing the four protocols, and understanding the mechanisms by which the PACP, the SRM4, and the COE early and modified editions code and grade the pipe segments with structural defects. In the introduction of this chapter, it was stated that the observations of that experiment should be verified by having them compared with a larger sample of sewer pipe segments.

In this section, the observations about the protocols' structural grading specified in the Section 4.4 are examined with the CCTV database structural grading results by each of the four protocols, shown in Figure 5.3.

- The PACP is the protocol which assigns lower structural grades to the pipe segments than the rest of the protocols: the PACP's averaging approach for structural grading results in lower structural grades for the inspected pipe segments than the SRM4 and the COE editions. This can be observed in the CCTV database grading results illustrated in Figure 5.3. The PACP grades more than 92% of the segments at the first three structural grades.
- The early edition of the COE has the most number of grade 5 pipe segments than all of the protocols: the CCTV database results conform to this statement. Twenty percent of the entire database receive a structural grade of "5" by the COE early edition and are classified as "failed".
- The modified edition of the COE results in high structural grades compared with the other three condition assessment protocols: Seventy one percent of the pipe segments in the CCTV database have received structural grades of "3", "4", and "5" by the COE modified edition. This number for the other three protocols is: The PACP with 7.4%, the SRM4 with 45.2%, and the COE early edition with 43%. Therefore this point is also in compliance with the CCTV grading results.
- The structural condition grading results by the four protocols show that a significant discrepancy exists among the protocols' condition assessment results: considering the structural grading results by the PACP, the SRM4,

and the COE early and modified edition, no similarities is observed. To consider this particular observation more in-depth, each two protocols' results on identical pipe segments are compared to each other pairwise and findings are discussed in the following section.

5.8 Pairwise Comparison of the Four Protocols

To be able to conduct a comprehensive comparison between the PACP, the SRM4, and the COE early and modified editions, their structural grading results for the same pipe segments should be studied. In this section, using the RDBMS queries, the protocols' grading results are compared to each other pairwise to figure out how close each pair grades the identical pipe segments, using the defect codes that the two protocols have in common. The queries are developed to list the pipe segments with each protocol's structural condition grading results, so that considering the similarities and differences is possible. The comparison findings are presented and discussed in Sections 5.8.1 to 5.8.6.

5.8.1 The PACP vs. the SRM4 Pairwise Comparison

The results of the pairwise comparison between the PACP and the SRM4 are presented in Table 5.1.

Table 5.1. The PACP vs. the SRM4 Pairwise Comparison Results

		PACP				
		1	**2**	**3**	**4**	**5**
SRM4	**1**	14.61%	0.00%	0.00%	0.00%	**0.00%**
	2	33.16%	6.73%	0.20%	0.09%	0.00%
	3	11.83%	6.15%	1.47%	0.08%	0.00%
	4	6.02%	10.47%	4.35%	0.43%	0.02%
	5	**1.72%**	1.88%	0.59%	0.07%	0.13%

Since the PACP uses an averaging method for structural grading, the final structural grades it assigns to the pipe segments are lower than the other protocols, including the SRM4. The PACP has graded only 3.81% of the records higher than the SRM4. While for 23.37% of the records the grading results are identical, approximately 44% of the records are graded with at least one grade of difference. However, the majority of the identical results belong to the first grade with slightly less than 15% of the records, leaving only less than 10% for all of the other four grades. Searching through approximately 2% of the pipe segments with extreme differences in the grading results, where the PACP results in a structural grading of 1 while the SRM4 grades the exact same pipe segment with 5, two major groups of cases are observed. First, the cases where the pipe segments contain a severe structural defect with the maximum deduct value; along with a high number of other low deduct value structural defects. The SRM4 grades the pipe segment based on the highest deduct value assigned to the structural defects. The PACP computes the average between one maximum deduct value and a large number of low deduct values which are assigned to the less important structural defects, which lower the final structural grading result. Therefore the very same pipe segment is rejected by the SRM4, and is in excellent conditions based on the PACP. The second group of extremely different grading results includes the cases, where severe displaced or separated joints exists, which the two protocols assign very different deduct values. The SRM4 assigns the maximum deduct values to such structural defects which results in the pipe segment’s rejection. The PACP assigns a deduct value of two out of five, which through the protocol's averaging method for final grade calculation results in the assessing the pipe to be in excellent conditions.

5.8.2 The PACP vs. the COE's Early Edition Pairwise Comparison

Comparing the PACP with the early edition of the COE, the results happen to have significant differences. Comparison results are illustrated in Table 5.2.

Table 5.2. PACP vs. COE Early Edition Pairwise Comparison Results

		PACP				
		1	**2**	**3**	**4**	**5**
COE Early Edition	**1**	16.17%	0.00%	0.00%	0.00%	**0.00%**
	2	30.03%	6.16%	0.07%	0.08%	0.00%
	3	6.58%	0.87%	0.02%	0.01%	0.00%
	4	7.99%	8.54%	2.07%	0.15%	0.01%
	5	**6.57%**	9.66%	4.45%	0.44%	0.14%

Almost 7% of the records which have received the grade of "5" by the early edition of the COE, are graded "1" by the PACP, which is a noticeable percentage for four grades of difference. Having considered these records, the PACP's averaging method for structural grade calculation seems to be the main reason for this excessive difference. Also, assigning high deduct values to sags by the COE's early edition, while the PACP does not consider sags as structural defects appears to be another reason for these extreme difference. Aside from approximately 16% of the records which are graded "1" by both of the protocols, only lesser than 7% of the pipe segments have received identical grades by both of the protocols. There are 33.5% of the entire database records which their structural grade difference by the two protocols is only one grade different. The PACP grades the pipe segments significantly lower than the COE early edition. 0.17% of the entire database has received higher grades by the PACP, compared with the COE early edition results.

5.8.3 The PACP vs. the COE's Modified Edition Pairwise Comparison

The comparison results for the PACP and the modified edition of the COE are very similar to the PACP versus the early edition of the COE as no specific consistency is observed in the protocols' results compared to each other. These results are shown in Table 5.3.

Table 5.3. PACP vs. COE Modified Edition Pairwise Comparison Results

		PACP				
		1	**2**	**3**	**4**	**5**
COE Modified Edition	**1**	19.37%	0.00%	0.00%	0.00%	**0.00%**
	2	11.40%	2.78%	0.02%	0.02%	0.00%
	3	21.32%	7.94%	0.90%	0.03%	0.00%
	4	9.17%	6.04%	1.08%	0.15%	0.00%
	5	**6.12%**	8.46%	4.58%	0.48%	0.14%

Approximately 20% of the pipe segments received an identical structural grade of 1, while slightly more than only 4% of records received identical grades of "2" to "5". Approximately 21% of the records have been graded with one grade of difference by the PACP and the COE's modified edition. Another point to notice in Table 5.3 is the notable portion of the pipe segments which are graded "1" by the PACP, and "3" by the COE's modified edition. More than 20% of the entire database belongs to this portion. The COE's modified edition grades the pipe segments much higher than the SRM4 or the COE's early edition in their comparison with the PACP. The COE modified edition assigns higher structural grades to 76.74% of the pipe segments compared to the PACP. More than 6% of the records have four grades of difference, mostly due to the PACP's averaging method of final structural grade calculation.

5.8.4 The SRM4 vs. the COE's Early Edition Pairwise Comparison

Table 5.4 illustrates the results of comparing SRM4 with the early edition of the COE. The interesting point about this comparison is that unlike the previous cases, the majority of the pipe segments which are graded identical by the two protocols have received a grade of 2, with 19.38% of the records. Almost 14% of the records are identically graded with 1, 3, 4, and 5 by the SRM4 and the COE early edition. Also, 56.56% of pipe segments are graded with one grade of difference, which makes the two protocols have the closest grading results compared with the comparisons conducted in Sections 5.8.1 to 5.8.3.

Table 5.4. SRM4 vs. COE Early Edition Pairwise Comparison Results

		SRM4				
		1	**2**	**3**	**4**	**5**
COE Early Edition	**1**	2.16%	13.97%	0.04%	0.00%	**0.00%**
	2	8.45%	19.38%	6.99%	1.52%	0.00%
	3	2.90%	3.51%	0.80%	0.24%	0.01%
	4	0.58%	1.55%	10.16%	6.39%	0.08%
	5	**0.53%**	1.76%	1.53%	13.15%	4.29%

While the COE's early edition grades 44% of the pipes higher than SRM4, the SRM4 grades almost 23% of pipe segments higher than the COE's early edition protocol. Very few of the records have extreme differences in the grades they have received by the two protocols with less than 1% of the database. The only major reason for the extreme difference is severe sags which the COE's early edition rejects them, and the SRM4 does not consider them as structural defects.

5.8.5 The SRM4 vs. the COE's Modified Edition Pairwise Comparison

The comparison results between the SRM4 and the COE's modified edition are illustrated in Table 5.5. Approximately 28% of the segments are graded identical by the SRM4 and the COE modified edition, and grade "3" pipe segments are the largest contributor to the percentage with 10.10%. Almost 58% of the records have only one level of difference in grading. The modified edition of COE assigns a higher grade to 43% of the pipe segments, which is approximately twice as big as the percentage of the pipe segments which the SRM4 grades higher with 23.82%. Similar to the comparison of the SRM4 and the COE early edition, sags are mostly the reason for the extreme four levels of grade difference existing in 1.41% of the records.

Table 5.5. The SRM4 vs. the COE Modified Edition Pairwise Comparison Results

		SRM4				
		1	**2**	**3**	**4**	**5**
COE Modified Edition	**1**	6.64%	12.69%	0.04%	0.00%	**0.00%**
	2	0.22%	8.86%	4.24%	0.90%	0.00%
	3	4.42%	11.48%	10.10%	4.16%	0.03%
	4	1.92%	4.69%	2.92%	5.13%	1.76%
	5	**1.41%**	2.48%	2.22%	11.09%	2.57%

5.8.6 The COE's Modified Edition vs. the COE's Early Edition Pairwise Comparison

The comparison results of the two editions of the COE protocol are not much closer to each other than the previous pairwise comparisons that have already been performed. More than 15% of the pipe segments are graded with two levels of grade difference or more. However, the two protocols have the highest percentage of identical grading with 43.52%, and only 10 pipe segments with four levels of difference. The modified edition grades the pipe segments slightly higher than the early edition. More than 33% of the pipe segments are graded higher by the COE's modified edition, while 22% of the pipe segments are graded higher by the early edition. The results are presented in Table 5.6.

Table 5.6. The COE Modified Edition vs. COE Early Edition Pairwise Comparison Results

		COE Modified Edition				
		1	**2**	**3**	**4**	**5**
COE Early Edition	**1**	11.04%	0.27%	8.48%	0.74%	**0.00%**
	2	5.68%	11.91%	14.16%	3.67%	0.82%
	3	0.03%	0.07%	3.33%	1.93%	1.54%
	4	0.00%	0.05%	9.60%	4.11%	2.71%
	5	**0.00%**	0.00%	0.03%	6.70%	13.13%

5.9 The COE Early and Modified Editions' Decisiveness of Parameters

The structural grading systems of the protocols, the PACP, the SRM4, and the COE early and modified editions were explained previously in Chapters 2 and 3. It was stated that the editions of the COE's protocol, calculate different parameters out of the deduct values they assign to the structural defects. By comparing these parameters with the pre-defined structural grading thresholds, the final structural grade of the pipe segment is the greatest grade resulted from the comparisons. The two editions have three parameters in common: The peak score, which is the greatest deduct value assigned to the pipe segment's defects. The total score, which is the summation of all of the deduct values assigned to the defects in the pipe segment. Finally, the mean score is calculated by dividing the total score by the pipe segment's length. The modified edition assigns higher structural grades to the pipe segment if structural defects of the same kind recur repeatedly along the pipe segment.

One of the capabilities of the designed relational database management system for this study is to determine which of the mentioned parameters decided the final structural condition grade that the COE editions assign to the pipe segment. Figure 5.4 illustrates how decisive each of the parameters is for the structural grades based on the early edition of the COE. If two or even all of the three parameters determine the structural grade of the pipe segment, all of them are considered to be equally decisive for the pipe's final grade.

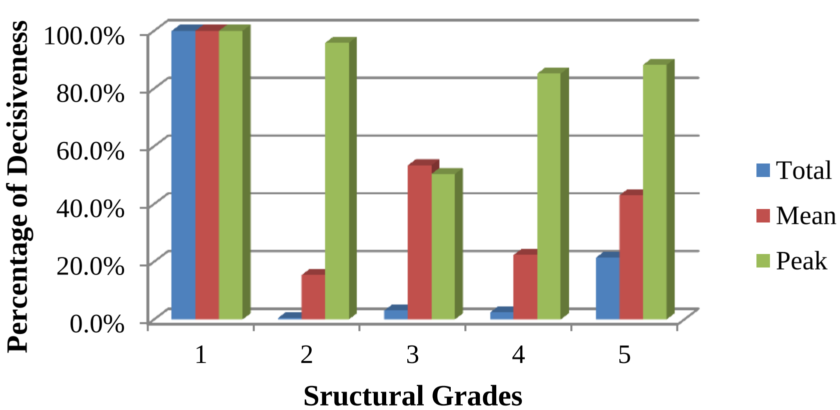

Figure 5.4. Decisiveness of Parameters in COE Early Edition

As shown in Figure 5.4, all of the peak, total, and mean scores are equally decisive for assigning grade “1” to the pipe segments based on the COE early edition. For grades “2” to “5”, the grades are decided mostly based on the pipe segments’ peak scores. However for grade “3”, peak and mean scores seem to share quite the same level of decisiveness for assigning the structural grade. Another observed point is how less decisive the total score is compared with the peak and mean scores. From Figure 5.4, it can be interpreted that the peak score structural grading thresholds are defined very highly in comparison mean, and especially total score thresholds by the COE early edition.

Figure 5.5 shows the COE modified edition’s parameters and their decisiveness for the final structural grading.

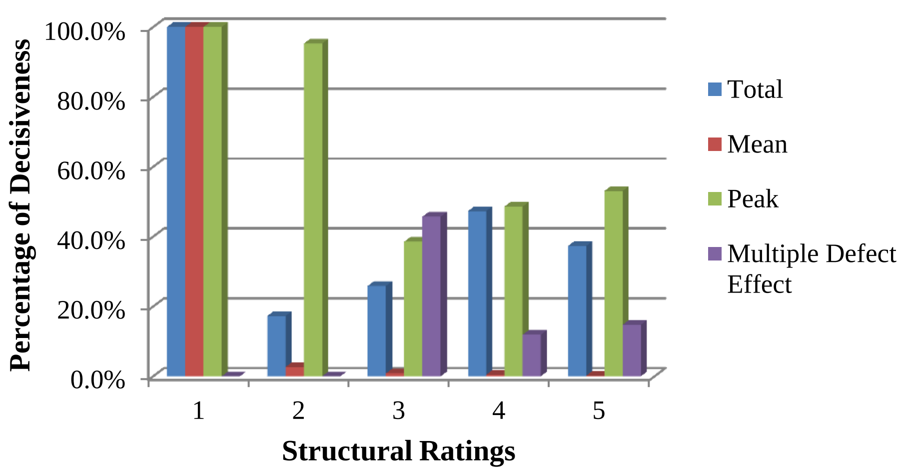

Figure 5.5. Decisiveness of Parameters in COE Modified Edition

Similar to the COE’s early edition, the first grade is equally determined by the three peak, mean, and total scores. The effectiveness of peak score has drastically been lowered by the changes which are made in the structural grading thresholds in the modified edition of the COE’s protocol compared to the earlier edition. In grades "3" and "4", the peak score equally shares the decisiveness with the multiple defect effect and the total score respectively. The modified structural grading thresholds have caused the total score to be effectively deciding the structural grades as opposed to the early edition. However, the mean score thresholds are defined so highly that its decisiveness could be almost neglected.

5.10 Summary

In Chapter 4, the PACP, the SRM4, and the COE early and modified editions were implemented in 20 pipe segment inspection surveys and results were analyzed. It was also stated that the results should be verified by having them compared with the assessment results of a large sample of pipe segments.

In doing so, a database of aged sewer pipe CCTV inspections, worth of 12 years of inspection from neighborhoods of Edmonton were used to implement the protocols in it. In order to manage the data and implement the protocols in the database, a relational database management system was developed in Microsoft Access 2010 medium. Using the structured query language, various features such as structural coding convertor, and structural grading comparison tools were added to the management system. The development procedure was explained in details in Section 5.4.2.

Having prepared the data and implemented each of the four protocols in the database, the grading results were presented in Section 5.6. The results of Chapter 4's experiment were compared with the database grading results, and full compliance between the database and 20 pipe segment experiments was noticed.

To analyze the trend consistency of the protocols' grading results, the result sets of each two protocols were compared pairwise.

It was observed from the results of the protocols' pairwise comparisons performed in Section 5.8 that the protocols barely grade the same pipe segments identical. The early and modified editions of the COE, with almost the same structural grading approaches grade slightly more than 40% of the pipe segments identical. This number becomes lower to almost 20% only if the first two structural grades are taken out of the consideration. The identicality percentages are drastically lower when the rest of the protocols are compared to each other. The factors contributing to the diversity and inconsistent assessment results by the four protocols are the main focus of Chapter 6.

Chapter 6: Validation of the Findings by Comparing the Protocols' Results with Expert Opinions

6.1 Introduction

Sewer pipes structural condition assessment protocols, the PACP, the SRM4, and the COE early and modified editions are different in certain manners. Their first difference is in their structural defect coding system, and the description each of the protocols provide for a particular structural defect. The deduct values which they assign to the structural codes vary as well. Finally, the methods used by the protocols to establish the final structural condition grade for the pipe segment, using the defects' deduct values differ from one protocol to another. These points were discussed in Chapter 3, where the PACP, the SRM4 and the COE editions were qualitatively compared.

In Chapters 4 and 5, the assessment results of these different protocols were considered, by implementing them in real experiment with 20 sewer pipe segments, and a database of aged sewer pipes CCTV database inspections. The effects of the aforementioned differences were studied with details by comparing the assessment results by the PACP, the SRM4, and the COE early and modified editions. The results show no specific consistency and each of the protocol's result sets have their properties, which are different than the rest.

The sewer structural condition assessment results are the principles of sewer network rehabilitative projects. Therefore, having altered results by different protocols means different rehabilitation prioritization. Hence, at this stage of the research, the accuracy of the assessment results is the valid question. Accuracy means how close the selected protocol's results are to the actual physical conditions of the sewer pipe. Or whether the assessment results generated by the selected protocol, is assigning higher priorities to the pipe segment which may survive longer than the pipe segments which in fact require urgent attention, and are not being addressed.

In this chapter, the aforementioned factors which are known to be the reasons for the protocols' different assessment results are validated by expert opinion. The factors within the PACP, the SRM4, and the COE early and modified editions are implemented in hypothetical cases, and are structurally graded by each of the protocols. Having graded the hypothetical cases by the four protocols, the results are compared with opinions which experts have on the physical conditions of the pipe segments. The comparison results are presented and discussed.

6.2 Assessment Discrepancy Factors and Hypothetical Implementation

From Chapters 3 to 5, the major reasons for the discrepant assessment results following the PACP, the SRM4, and the COE early and modified editions can be summarized as follows:

- The PACP's averaging method for computation of the pipe segment's structural condition grade.
- The COE's structural defect category "sag", which is not defined by the PACP or the SRM4.
- The COE early edition's peak score structural grading thresholds.

- Recording of spiral fractures/cracks as circumferential or longitudinal fractures/cracks by the COE early and modified editions' coding systems.
- The COE modified edition's total score structural grading thresholds.
- Lack of various severity levels for certain structural defects in the COE editions' coding systems.
- The PACP and the COE modified edition's deduct values for severely separated joints.

These factors are implemented in eight hypothetical cases. The cases are not selected from the real-world surveys or the database records, so that the focus of the assessment is exclusively on the implemented factor. No specific length, pipe diameter, or sewer system type is defined for the cases, as they do not affect the pipe's structural condition grading based on any of the four protocols. The cases are presented in Table 6.1.

Table 6.1. Description of Hypothetical Cases

	Description of Defects		
Case #	**Defect 1**	**Defect 2**	**Defect 3**
1	pipe is severely fractured and deformed with heaved crown for one meter, and ovality is approximately more than 40%.	Longitudinal Crack for one meter	Longitudinal Crack for one meter
2	Pipe is slightly sagged out and water stays at the same level for approximately 80 meters	Light Open Joint	Light Open Joint
3	pipe is severely fractured for approximately one meter at crown. Pipe is totally intact, with no ovality or area loss	Circumferential Crack	
4	Longitudinal Fracture for one and a half meters		

Table 6.1. Description of Hypothetical Cases, Cont'd

	Description of Defects		
Case #	**Defect 1**	**Defect 2**	**Defect 3**
5	in the defect zone, there exists a fracture which spins around the virtual longitudinal axis of the pipe and changes direction both longitudinally and circumferentially, and is one and half meters long. The defect affects three quadrants of the pipe except for 9 o'clock to 12 o'clock	Circumferential Crack	
6	severe cracks with alligator pattern for about 2.1 meters of length	Severe cracks with alligator pattern for approximately 1.2 meters of length and cracks are likely to open up and transform to fractures	Longitudinal Crack for 14.1 meters
7	hole with radial extent lesser than quadrant at the right half of the pipe		
8	an open joint which the soil underneath the pipe is clearly visible		

The hypothetical cases described in Table 6.1 are structurally graded by the PACP, the SRM4, and the COE early and modified editions. Table 6.2 illustrates the results.

Table 6.2. The Protocols' Assessment Results for Hypothetical Cases

Case #	PACP	SRM4	COE Early Ed.	COE Modified Ed.
1	2	5	5	5
2	1	2	1	5
3	2.5	4	5	4
4	3	3	4	3
5	2	3	4	3
6	3	3	4	4
7	4	4	5	5
8	2	4	5	5

6.3 Expert Opinions and Analysis of the Protocols' Assessment Results

Two experts' opinions on the structural conditions of the described hypothetical cases are presented in Table 6.3. The experts were asked to assign a grade from one to five to each of the hypothetical cases only based on the case's anticipated remaining useful life, independent from any condition assessment protocols.

Table 6.3. Expert Opinions on the Hypothetical Cases

Case #	Expert 1	Expert 2
1	5	5
2	2	2
3	3, If there is water table fluctuation, inflow/infiltration, surcharging history, and the pipe is in risky soil it could potentially be rated higher and should be inspected with more care	3 or 4
4	3	3
5	4	4
6	3, Since the severely cracked spot is likely to open up	3, The entire pipe seems to be subjected to an external load
7	4	4, No void is inspected
8	5, The bedding of the pipe segment should also be studied as well as its casing, if there is any	5

Comparing the physical conditions which the experts believe the hypothetical pipe segments are in, with the results obtained by the PACP, the SRM4, and the COE early and modified editions, the following facts could be pointed out regarding each of the cases:

Case #1: Apparently, the PACP is not providing a pertinent assessment of the actual structural condition of this pipe segment. All of the mentioned defects have been predicted in its coding system, and the deduct values assigned to each of the defects, 5 for the severely fractured and deformed spot and 1 for the cracks seem to be relevant. However, the PACP's averaging method to calculate the final structural grade for the pipe segment alters the result.

The SRM4 and both the COE editions' are in compliance with the expert judgements.

Case #2: The PACP does not consider sag as a structural defect and the deduct values which are assigned to each of the defects are 1. Therefore, the final structural condition grading of the pipe based on the PACP is 1.

Although the early edition of COE considers sag as a structural defect, the final condition grading which is calculated for this by this protocol is 1, based on the defect's deduct value and the COE early edition's structural grading thresholds. The modified edition of the COE fails this pipe segment. Considering the length of the inspected sag, the total score structural grading thresholds defined by the protocol results in a grade of 5.

Based on the SRM4, when cracks appear on the internal wall of the pipeline, it means that the pipe is under unbalanced external forces. Therefore the pipe is not at its excellent structural conditions and it is assigned a grade of 2.

Case #3: The early edition of the COE has a 115 deduct value scale for its structural condition grading. However, the required peak score to reject a pipe segment in the structural thresholds table is only 5 and therefore the pipe segment is rejected based on this protocol.

The PACP grades this pipe with 2.5 which clearly is not a reliable description of the pipe's actual physical state and downgrades its structural conditions.

Both of the SRM4 and the modified edition of the COE grade this pipe segment 4 structurally which are the closest of the four protocols to the expert opinions.

Case #4: The deduct value assigned to a longitudinal fracture by the COE early edition is 4. Its peak score structural grading thresholds result in a final grade of 4 for the pipe segment with a peak score of 4. However, a longitudinal fracture barely could be considered as a sing of "near-to-fail" physical condition. The rest of the protocols assess the pipe segment, consistent with the experts' opinion for the pipe's structural state.

Case #5: None of the editions of the COE protocol properly address spiral fractures/cracks and code them as circumferential or longitudinal defects. Hence, both of the COE early and modified editions assign lower deduct values to spiral fractures/cracks than what these defects deserve, which results in structural grades which are not reflecting the pipe segments' structural state properly.

Also, the PACP's averaging method for computing the final structural grade is the reason for the difference between its assessment result and the experts' opinion.

Case #6: The early edition of the COE assigns a deduct value of 4 to severe cracking, which results in a final structural grade of 4 for the pipe segment through its structural grading thresholds. In the modified edition of the protocol, the deduct value for severe cracking has been revised, however, its total score structural grading thresholds decide this pipe segment to be at grade 4.

The PACP's averaging method for computing the pipe segment's final structural grade has its effect in downgrading the actual structural condition of the pipe.

The SRM4, grades this pipe structurally 3, which is the most accurate of the four for this case.

Case #7: Both editions of the COE reject this pipe segment due to the presence of the hole, broken pipe as interpreted by the early edition, without taking the extent of the hole into the account. The PACP and the SRM4 structural grades are matching with the experts' opinion about this pipe segment.

Case #8: Disconnection of the joints, to the level that the soil beyond the joints is visible means that the network does not exist anymore and the pipe segments are totally dislodged from their place. Therefore this matter should immediately be taken care of and could be classified as a cause for failure.

Neither of the COE modified edition or the PACP do not address this issue properly and result in grades other than 5. The early edition of the city's standard and the SRM4 reject the pipe segment and require that it should be rehabilitated immediately.

6.4 Summary

In this chapter, the factors which were believed to be the reasons for discrepant structural grading results by the PACP, the SRM4, and the COE early and modified editions were pointed out. Having applied these factors in hypothetical case scenarios, the protocols' assessment results for the cases were compared to the opinions obtained from the industry experts.

Each of the studied condition assessment protocols, the PACP, the SRM4, and the COE early and modified editions seem to have their inconsistencies in terms of properly reflecting the structural defects and grading the pipe segments based on the defects' deduct values. The SRM4 seems to be an exception to this statement with all of its responses being the closest of the four protocols to the expert opinions.

The mentioned inconsistencies exist in the protocols' coding systems, their deduct values, and their structural grade computation approach which result in grades which are not consistent with the pipe segments' actual structural conditions. This matter reduces the trust in the protocols which deal with such inconsistencies since major decisions for maintaining the sewer networks are made based on their assessment results. If assessment results do not match with the pipes segments' real structural state, priorities which are assigned to different sections of the sewer network for rehabilitative actions are not reliable.

Chapter 7: Conclusions and Recommendations

7.1 General Summary

This study focused on the accuracy and reliability of the sewer pipes structural condition assessment protocols, the PACP, the SRM4, and the COE early ad modified editions. The condition assessment protocol is the foundation of sewer rehabilitation and maintenance plans which are designed and executed by municipalities. The importance and necessity of having a sewer condition assessment protocol as the key element of any asset management program was thoroughly considered in the state of the art. The existing structural condition assessment protocols which are currently being utilized in Canada were described. The aforementioned four sewer condition assessment protocols were compared to each other from a qualitative point of view. In the third chapter, their coding and assessment approaches were examined by implementing each of them in 20 pipe segment inspection surveys in Chapter 4. The findings of this section were compared with structural assessment results of a CCTV inspection database in Chapter 5, using a relational database management system which is developed exclusively for this purpose. The management system is equipped with features capable of converting the protocols' coding systems to each other. The assessment outcomes of the protocols were comprehensively compared to each other by adopting pairwise comparison approach and the factors causing the differences were investigated.

Possible inconsistencies of each of the protocols in their coding systems, defects' deduct values, and their structural condition grading methods were implemented in hypothetical case scenarios in chapter 6. The assessment results obtained by each of the PACP, the SRM4, and the COE early and modified editions were examined through comparison with expert judgments in order to validate the findings, being the factors causing the discrepant assessment results. The results of this stage helped understand which protocol properly addresses the actual physical condition of the considered pipe segment. A summary of the findings of this study and presented in the following section, as well as suggestions for future research.

7.2 Conclusions

- There are certain categories of structural defects which are considered by some of the protocols and are totally neglected by some others. This matter has a noticeable effect on the final outcome of the assessments. A good instance for this point is "sag", which is considered to be a structural defect by both editions of the City of Edmonton's protocol and are not taken into account by either of the PACP or the SRM4.
- The protocols differ in the level of detail by which they describe certain defect categories.
- The assessment results of the protocols have fundamental difference. In a pairwise comparison approach, the results of each pair of the protocols are barely identical for 30% of the considered cases.

- The NASSCO PACP is the least conservative protocol in comparison with the other three protocols. The averaging system which this protocol uses to determine the final grade of the considered pipe segments downgrades the actual condition of the assessed pipe.
- The WRc SRM4 appears to have the highest level of compliance with the assessed pipe segments' actual structural conditions. The protocols' responses to the hypothetical cases were the closest of all the protocols to the expert opinions

7.3 Recommendations for Future Research

The assessment results, in comparison with the expert opinions illustrate the need to optimize the assessment protocols which their inconsistencies were pointed out in areas such as coding systems, deduct values, and structural grade computation methods.

The following recommendations are suggested for future work:

- Executing a comparison on the operational and maintenance related defects and their assessment criteria.
- More involvement of the physical characteristics of the pipe segments, such as their sewer system type, their material, and their length and diameter.
- Studying the effects of proper installation and appropriate bedding of the pipe on its long term structural performance, and reflecting this in the assessment and prioritization of the pipe segments in the protocols.

References

Allouche, E. N., Freure, P. (2002). “Management and maintenance practices of storm and sanitary sewers in Canadian Municipalities.” ICLR Research Paper Series – No.18.

American Society of Civil Engineers (ASCE). (2001). “Evaluation of SSET: the sewer scanner and evaluation technology.” Printed in the USA.

Bainbridge, K., Dover, S., Maruccio, F., McDonald, S., and Potvin., D. (2012). “Condition Assessment and Management of Critical Watermains in the City of Ottawa.” North American Society for Trenchless Technology (NASTT) No-Dig Show 2012 Proceedings. Nashville, TN, USA.

Beck, D. E. (2008). “The Social and Economic Aspects of No-Dig Pipeline Technologies.” UMI Journal of Finance and Management for Water and Wastewater Professionals, Sep/Oct 2008, 21 – 23.

Canada’s Civil Infrastructure Systems. (2003) “Civil Infrastructure Systems: Technology Road Map 2003 – 2013.”

Canadian Water and Wastewater Association. (1998). “Municipal Water and Wastewater Infrastructure: Estimated Investment Need 1997 to 2012.”

Canada West Foundation. (2003). “Canada West Foundation 2003 Annual Report.” Calgary, AB, Canada.

Cascante, G., Knight, M., and Lopez, M.C. (2001). “Laboratory investigation into the assessment of concrete pipes state of deterioration using ultrasonic testing techniques.” The 2001 International Conference on Underground Infrastructure Research Proceedings; Kitchener, ON, Canada.

Crowder, D. (2011). “How the City of Hamilton tackled a major sewer repair and rehabilitation project.” The Ontario Technologist, January/February 2011. Toronto, ON, Canada.

Federation of Canadian Municipalities. (2006). “Building Prosperity from the Ground up: Restoring Municipal Fiscal Balance.” June 2006. Ottawa, ON, Canada.

Feeney, C. S., Thayer, S., Bonomo, M., and Martel, K. (2009). “White Paper on Condition Assessment of Wastewater Collection Systems.” U.S. Environmental Protection Agency Report No. EPA/600/R-09/409. Cincinnati, OH, USA.

Harchaoui, T. M., Tarkhani, F., Warren, P. (2003). “Public Infrastructure in Canada: Where Do We Stand?” Statistics Canada. Catalogue No. 11-624-MIE. Ottawa, ON, Canada.

Jones, C., Lewis, D. (2012). “Advances in Water Pipeline Condition Assessment.” North American Society for Trenchless Technology (NASTT) No-Dig Show 2012 Proceedings. Nashville, TN, USA.

Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Ambrose, M., Madin, B., and Fitsgerald, A. (2007). “Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets.” Water Environment Research Foundation (WERF). London, UK.

McDonald, S. E., Zhao, J. Q. (2001). “Condition Assessment and Rehabilitation of Large Sewers.” National Research Council Canada Report No. NRCC-44696. Ottawa, ON, Canada.

Mellet, J.S. (1995). “Ground Penetrating Radar Applications in Engineering, Environmental Management, and Geology.” Journal of Applied Geophysics, Vol. 33, New York, USA.

Mirza, M. S. (2007). “Danger Ahead: The Coming Collapse of Canada’s Municipal Infrastructure.” Federation of Canadian Municipalities, Ottawa, ON, Canada.

Mirza, M. S., Haider, M. (2003). “The State of Infrastructure in Canada: Implications for Infrastructure Planning and Policy.” McGill University. Montreal, QC, Canada.

North American Association of Pipeline Inspectors (NAAPI). (2003). “North American Association of Pipeline Inspectors Training Manual”. Waterloo, ON, Canada.

National Asset Management Working Group. (2009). “An Asset Management Governance Framework for Canada.” National Round Table for Sustainable Infrastructure. Retrieved from: http://www.nrtsi.ca/documents/An%20Asset%20Management%20Framework%20v8Feb09.doc

National Association of Sewer Service Companies (NASSCO) (2001). "Pipeline Assessment Certification Manual.", Dallas, TX, USA.

National Research Council Canada (NRC). (2004). “Municipal Infrastructure Planning (MIIP) Report: An Evaluation of Condition Assessment Protocols for Sewer Management.” Report No. B – 5123.6. Ottawa, ON, Canada.

Opina, M. C. (2010). “ Structural Condition Scoring of Buried Sewer Pipes for Risk-Based Decision Making.” Doctoral Dissertation. University of Delaware. Newark, DE, USA.

Read, G. F., Vickridge, I. (1997). “Sewers; Rehabilitation and New Construction: Repair and Renovation.” Elsevier Butterworth-Heinemann, Oxford, UK.

Sibbald, A., Fairfield, C.A., and Forde, M.C. (1995). “Impulse Testing of Brickwork Sewers.” Journal of Low Frequency Noise & Vibration, 1995, Vol. 14, No.1.

The City of Edmonton (1996). "Sewer Physical Condition Classification Manual." Edmonton, AB, Canada.

The City of Edmonton (1996). "Standard Sewer Condition Rating System Report." Edmonton, AB, Canada.

The City of Edmonton (2010). "Final Manual: Structural Condition Rating System." Edmonton, AB, Canada.

Water Environment Federation. (2009). “Existing Sewer Evaluation and Rehabilitation, Third Edition.” McGraw-Hill Companies, Inc. Printed in USA.

Weil, G.J. (1998). “Non-Destructive Testing of Large Concrete Structures.” The International Society for Optics and Photonics Conference 1998 Proceedings. SPIE 3397. San Antonio, TX, USA.

APPENDIX A. PACP Coding Matrix

Table A.1. PACP Coding Matrix

Family	**Group**	**Descriptor**	**Modifier**	**Code**	**Structural Grade**
Structural	Crack (C)	Circumferential (C)		CC	1
		Longitudinal (L)		CL	2
		Multiple (M)		CM	3
		Spiral (S)		CS	2
Structural	Fracture (F)	Circumferential (C)		FC	2
		Longitudinal (L)		FL	3
		Multiple (M)		FM	4
		Spiral (S)		FS	3
Structural	Pipe Failure (Silent)	Broken (B)		B	1 clock pos: 3, 2 clock pos: 4, >=3 clock pos:5
		Broken (B)	Soil Visible (SV)	BSV	5
		Broken (B)	Void Visible (VV)	BVV	5
		Hole (H)		H	1 clock pos: 3, 2 clock pos: 4, >=3 clock pos:5
		Hole (H)	Soil Visible (SV)	HSV	5
		Hole (H)	Void Visible (VV)	HVV	5
Structural	Collapse (X)	Pipe (P)		XP	5
		Brick (B)		XB	5
Structural	Deformed (D)	(Pipe) (P)		D	<=10%: 4, >10%: 5
		Brick (B)	Horizontally (H)	DH	5
		Brick (B)	Vertically (V)	DV	5
Structural	Joint (J)	Offset (displaced) (O)	Med (M)	JOM	1
			Large (L)	JOL	2
		Separated (open) (S)	Med (M)	JSM	1
			Large (L)	JSL	2
		Angular (A)	Med (M)	JAM	1
			Large (L)	JAL	2

Table A.1. PACP Coding Matrix, Cont'd

Family	**Group**	**Descriptor**	**Modifier**	**Code**	**Structural Grade**
Structural	Surface Damage Chemical (S)	Roughness Increased (RI)	C	SRIC	1
		Surface Spalling (SS)	C	SSSC	2
		Aggregate Visible (AV)	C	SAVC	3
		Aggregate Projecitng (AP)	C	SAPC	3
		Aggregate Missing (AM)	C	SAMC	4
		Reinforcement Visible (RV)	C	SRVC	5
		Reinforcement Corroded (RC)	C	SRCC	5
		Missing Wall (MW)	C	SMWC	5
		Other (Z)	C	SZC	
Structural	Surface Damage Mechanical (M)	Roughness Increased (RI)	M	SRIM	1
		Surface Spalling (SS)	M	SSSM	2
		Aggregate Visible (AV)	M	SAVM	3
		Aggregate Projecting (AP)	M	SAPM	3
		Aggregate Missing (AM)	M	SAMM	4
		Reinforcement Visible (RV)	M	SRVM	5
		Reinforcement Corroded (RC)	M	SRCM	5
		Missing Wall (MW)	M	SMWM	5
		Other (Z)	M	SZM	N/A
Structural	Surface Damage Not Evident (Z)	Roughness Increased (RI)	Z	SRIZ	1
		Surface Spalling (SS)	Z	SSSZ	2
		Aggregate Visible (AV)	Z	SAVZ	3
		Aggregate Projecting (AP)	Z	SAPZ	3
		Aggregate Missing (AM)	Z	SAMZ	4
		Reinforcement Visible (RV)	Z	SRVZ	5
		Reinforcement Corroded (RC)	Z	SRCZ	5
		Missing Wall (MW)	Z	SMWZ	5
		Other (Z)	Z	SZZ	N/A
Structural	Surface Damage (Metal Pipes)	Corrosion (CP)		SCP	3
		Detached (D)		LFD	3

Table A.1. PACP Coding Matrix, Cont'd

Family	**Group**	**Descriptor**	**Modifier**	**Code**	**Structural Grade**
		Defective End (DE)		LFDE	3
		Blistered (B)		LFB	3
		Service Cut Shifted (CS)		LFCS	3
		Abandoned Connection (AC)		LFAC	
		Overcut Service (OC)		LFOC	3
		Undercut Service (UC)		LFUC	3
		Buckled (BK)		LFBK	3
		Wrinkled (W)		LFW	3
		Other (Z)		LFZ	
Structural	Weld Failure (WF)	Circumferential (C)		WFC	2
		Longitudinal (L)		WFL	2
		Multiple (M)		WFM	3
		Spiral (S)		WFS	2
Structural	Point Repair (PR)	Localized Lining (L)		RPL	
		Localized Lining (L)	Defective (D)	RPLD	4
		Patch Repair (P)		RPP	
		Patch Repair (P)	Defective (D)	RPPD	4
		Pipe Replaced (R)		RPR	
		Pipe Replaced (R)	Defective (D)	RPRD	4
		Other (Z)		RPRZ	
		Other (Z)		RPRZD	
Structural	Brickwork (Silent)	Displaced (DB)		DB	3
		Missing (MB)		MB	4
		Dropped Invert (DI)		DI	5
		Missing Mortar	Slight	MMS	2
			Medium	MMM	3
			Large	MML	3

APPENDIX B. WRc SRM4 S Defect Score Table

Table B.1. WRc SRM4 Defect Score Table

	Code	Description	Score
Cracks	CC	Crack Circumferential	10
	CL	Crack Longitudinal	10
	CM	Crack Multiple	40
	CS	Crack Spiral	40
Fractures	FC	Fracture Circumferential	40
	FL	Fracture Longitudinal	40
	FM	Fracture Multiple	80
	FS	Fracture Spiral	80
Broken	B	Broken Pipe	80
Hole	H	Hole, Radial Extent <1/4	80
		Hole, Radial Extent >1/4	165
Deformations	D	0 – 5%	20
		5 – 10%	80
		> 11%	165
Collapsed	XP	Collapsed Sewer	165
Joints	JDM	Joint Displaced Medium	1
	JDL	Joint Displaced Large	2
	JDSV	Joint Displaced Soil Visible	80
	OJM	Open Joint Medium	1
	OJL	Open Joint Large	2
	OJSV	Open Joint Soil Visible	165
Spalling/ Wear	SWS	Surface Wear Slight	5
	SWM	Surface Wear Medium	20
	SWL	Surface Wear Large	120

APPENDIX C. The COE Early Edition Defect Weight Table

Table C.1. The COE Early Edition Defect Weight Table

Defect	**Code**	**Unit**	**Weight**
Cracks			
- Light	CL	each	1
- Moderate	CM	meter	2
- Severe	CS	meter	4
Fractures			
- Light	FL	each	2
- Moderate	FM	meter	4
- Severe	FS	meter	5
Broken Pipe			
Broken (Pieces Broken Away)	FX	each	110
Deformed Pipe			
- Light (minimal loss of area)	DL	meter	2
- Moderate (loss of area ≤ 10%)	DM	meter	4
- Severe (10% < loss of area ≤ 25%)	DS	meter	100
Collapsed Pipe			
Collapsed (loss of structural integrity, loss of area > 25%)	DX	meter	115
Open Joints			
- Light (less than 25 mm)	OL	each	1
- Moderate (*25 - 100 mm)*	OM	each	2
- Severe (greater than 100 mm)	OS	each	5
Joint Displacement			
- Light (less than a wall thickness)	JL	each	2
- Moderate (area loss up to 25%)	JM	each	3
- Severe (area loss greater than 25%)	JS	each	100
Sags			
- Light (ponded water)	SL	meter	1
- Moderate (camera partially submerged)	SM	meter	2
- Severe (camera completely submerged)	SS	meter	20
Surface Damage			
- Light (light exposed aggregate)	HL	meter	1
- Moderate (exposed aggregate)	HM	meter	2
- Severe (exposed steel reinforcement)	HS	meter	4

APPENDIX D. The COE Modified Edition Defect Weight Table

Table D.1. The COE Modified Edition Defect Weight Table

Defect	**Code**	**Unit**	**Weight**
Crack			
Light	CL	Meter	10
Moderate	CM	Meter	37
Severe	CS	Meter	54
Fracture			
Light	FL	Meter	33
Moderate	FM	Meter	68
Severe	FS	Meter	84
Broken Pipe			
Light	FXL	Each	41
Moderate	FXM	Each	73
Light Void	FXVL	Each	86
Severe Void	FXVS	Each	100
Hole			
Light	FXVL	Each	86
Severe	FXVS	Each	100
Deformation			
Light	DL	Meter	34
Moderate	DM	Meter	70
Severe	DS	Meter	91
Collapsed Pipe			
Collapsed Pipe	DX	Meter	100
Joint Displacement			
Light	JL	Each	28
Moderate	JM	Each	59
Severe	JS	Each	79
Open Joint			
Light	OL	Each	25
Severe	OS	Each	72
Sag			
Light	SL	Meter	25
Severe	SS	Meter	76
Surface Damage			
Light	HL	Meter	21
Moderate	HM	Meter	53
Severe	HS	Meter	76

Table D.1. The COE Modified Edition Defect Weight Table, Cont'd

Defect	**Code**	**Unit**	**Weight**
Lining			
Abandoned Connection	LAC	Each	42
Overcut Service	LOC	Each	64
Undercut Service	LUC	Each	56
Lining – Wrinkled	LW	Meter	62
Lining – Other Defects	LZ	Meter	65

APPENDIX E. 20 Pipe Segment CCTV Reviews

E.1. Case Number 1

Pipe Length: 89.95 m

Sewer System: Combined

Pipe Diameter 375 mm

E.1.1. The PACP

Coding:

Table E.1. Case Number 1 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5	3	2	FL	Longitudinal Fracture	3
7.4	8.2	1	FL	Longitudinal Fracture	3
9.8	12	3	CL	Longitudinal Crack	2
13.4	14.2	1	FL	Longitudinal Fracture	3
15	16.4	2	CL	Longitudinal Crack	2
17.5	20	3	FL	Longitudinal Fracture	3
25.9	27	2	FL	Longitudinal Fracture	3
27.5	28.6	2	FS	Spiral Fracture	3
29.2	30.3	2	FL	Longitudinal Fracture	3
30.5	31	1	FL	Longitudinal Fracture	3
33.5	34.1	1	FL	Longitudinal Fracture	3
35.2	37	2	FL	Longitudinal Fracture	3
40	40.4	1	FL	Longitudinal Fracture	3
40.6	41.3	1	FC	Circumferential Fracture	2
42	43	1	FC	Circumferential Fracture	2

Structural Condition Grading:

Segment Grade 2 Score: 14

Segment Grade 3 Score: 54

Structural Pipe Rating: 68

Structural Pipe Rating Index: 2.72 ≈ 3

E.1.2. The SRM4

Coding:

Table E.2. Case Number 1 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Defect Score
1.5	3	FL	Fracture Longitudinal	40
7.4	8.2	FL	Fracture Longitudinal	40
9.8	12	CL	Crack Longitudinal	10
13.4	14.2	FL	Fracture Longitudinal	40
15	16.4	CL	Crack Longitudinal	10
17.5	20	FL	Fracture Longitudinal	40
25.9	27	FL	Fracture Longitudinal	40
27.5	28.6	FS	Fracture Spiral	80
29.2	30.3	FL	Fracture Longitudinal	40
30.5	31	FL	Fracture Longitudinal	40
33.5	34.1	FL	Fracture Longitudinal	40
35.2	37	FL	Fracture Longitudinal	40
40	40.4	FL	Fracture Longitudinal	40
40.6	41.3	FC	Fracture Circumferential	40
42	43	FC	Fracture Circumferential	40

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.1.3. The COE Early Edition

Coding:

Table E.3. Case Number 1 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	3	1.5	FM	Fracture Moderate	4	6
7.4	8.2	0.8	FM	Fracture Moderate	4	3.2
9.8	12	2.2	CM	Crack Moderate	2	4.4
13.4	14.2	0.8	FM	Fracture Moderate	4	3.2
15	16.4	1.4	CM	Crack Moderate	2	2.8

Table E.3. Case Number 1 COE Early Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
17.5	20	2.5	FM	Fracture Moderate	4	10
25.9	27	1.1	FM	Fracture Moderate	4	4.4
27.5	28.6	1.1	FM	Fracture Moderate	4	4.4
29.2	30.3	1.1	FM	Fracture Moderate	4	4.4
30.5	31	0.5	FM	Fracture Moderate	4	2
33.5	34.1	0.6	FM	Fracture Moderate	4	2.4
35.2	37	1.8	FM	Fracture Moderate	4	7.2
40	40.4	0.4	FM	Fracture Moderate	4	1.6
40.6	41.3	0.7	FL	Fracture Light	2	1.4
42	43	1	FL	Fracture Light	2	2

Structural Condition Grading:

Total Score: 59.4

Mean Score: 0.66

Peak Score: 4

Structural Condition Rating: 4

E.1.4. The COE Modified Edition

Coding:

Table E.4. Case Number 1 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	3	1.5	FM	Moderate Fracture	3	68	102
7.4	8.2	0.8	FM	Moderate Fracture	3	68	54.4
9.8	12	2.2	CM	Crack Moderate	2	37	81.4
13.4	14.2	0.8	FM	Moderate Fracture	3	68	54.4
15	16.4	1.4	CM	Crack Moderate	2	37	51.8
17.5	20	2.5	FM	Moderate Fracture	3	68	170
25.9	27	1.1	FM	Moderate Fracture	3	68	74.8
27.5	28.6	1.1	FM	Moderate Fracture	3	68	74.8

Table E.4. Case Number 1 COE Modified Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
29.2	30.3	1.1	FM	Moderate Fracture	3	68	74.8
30.5	31	0.5	FM	Moderate Fracture	3	68	34
33.5	34.1	0.6	FM	Moderate Fracture	3	68	40.8
35.2	37	1.8	FM	Moderate Fracture	3	68	122.4
40	40.4	0.4	FM	Moderate Fracture	3	68	27.2
40.6	41.3	0.7	FL	Light Fracture	1	33	23.1
42	43	1	FL	Light Fracture	1	33	33

Structural Condition Grading:

Total Score: 1018.9

Mean Score: 11.33

Peak Score: 68

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.2. Case Number 2

Pipe Length: 113.04 m

Sewer System: Combined

Pipe Diameter 200 mm

E.2.1. The PACP

Coding:

Table E.5. Case Number 2 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.6	3.3	2	FS	Spiral Fracture	2
9.5	12	3	SRIC	Chemical Surface Damage, Roughness Increased	1

Table E.5. Case Number 2 PACP Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
12.6	13	1	CL	Longitudinal Crack	2
17.6	18.6	1	FM	Multiple Fracture	4
45	46.2	2	FS	Spiral Fracture	2
52.2	55	3	CL	Longitudinal Crack	2
66.3	67.8	2	CS	Spiral Crack	2
71	72.2	2	CM	Multiple Crack	3
72.5	74.4	2	FL	Longitudinal Fracture	3
77.9	79	2	FS	Spiral Fracture	2
79.5	80	1	FM	Multiple Fracture	4
98	99.1	2	FS	Spiral Fracture	2
110.3	111	1	CC	Circumferential Crack	1
111	111.2	1	FC	Circumferential Fracture	2
111	112.5	2	CL	Longitudinal Crack	2

Structural Condition Grading:

Segment Grade 1 Score: 4

Segment Grade 2 Score: 34

Segment Grade 3 Score: 12

Segment Grade 4 Score: 8

Structural Pipe Rating: 58

Structural Pipe Rating Index: 2.15 ≈ 2

E.2.2. The SRM4

Coding:

Table E.6. Case Number 2 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.6	3.3	FS	Fracture Spiral	80
9.5	12	SWS	Surface Wear Slight	5
12.6	13	CL	Crack Longitudinal	10

Table E.6. Case Number 2 SRM4 Defect Coding, Cont'd

Dist	Dist_to	Code	Description	Unit Score
17.6	18.6	FM	Fracture Multiple	80
45	46.2	FS	Fracture Spiral	80
52.2	55	CL	Crack Longitudinal	10
66.3	67.8	CS	Crack Spiral	40
71	72.2	CM	Crack Multiple	40
72.5	74.4	FL	Fracture Longitudinal	40
77.9	79	FS	Fracture Spiral	80
79.5	80	FM	Fracture Multiple	80
98	99.1	FS	Fracture Spiral	80
110.3	111	CC	Crack Circumferential	10
111	111.2	FC	Fracture Circumferential	40
111	112.5	CL	Crack Longitudinal	10

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.2.3. The COE Early Edition

Coding

Table E.7. Case Number 2 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.6	3.3	1.7	FM	Fracture Moderate	4	6.8
9.5	12	2.5	HL	Surface Damage Light	1	2.5
12.6	13	0.4	CM	Crack Moderate	2	0.8
17.5	18.5	1	SM	Sag Moderate	2	2
17.6	18.6	1	FS	Fracture Severe	5	5
45	46.2	1.2	FM	Fracture Moderate	4	4.8
52.2	55	2.8	CM	Crack Moderate	2	5.6
66.3	67.8	1.5	CM	Crack Moderate	2	3

Table E.7. Case Number 2 COE Early Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
71	72.2	1.2	CS	Crack Severe	4	4.8
72.5	74.4	1.9	FM	Fracture Moderate	4	7.6
77.5	78.5	1	SM	Sag Moderate	2	2
77.9	79	1.1	FM	Fracture Moderate	4	4.4
79.5	80	0.5	FS	Fracture Severe	5	2.5
98	99.1	1.1	FM	Fracture Moderate	4	4.4
110.3	111	0.7	CL	Crack Light	1	0.7
111	111.2	0.2	FL	Fracture Light	2	0.4
111	112.5	1.5	CM	Crack Moderate	2	3

Structural Condition Grading:

Total Score: 60.3

Mean Score: 0.53

Peak Score: 5

Structural Condition Rating: 5

E.2.4. The COE Modified Edition

Coding:

Table E.8. Case Number 2 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.6	3.3	1.7	FM	Moderate Fracture	3	68	115.6
9.5	12	2.5	HL	Light Surface Damage	1	21	52.5
12.6	13	0.4	CM	Crack Moderate	2	37	14.8
17.5	18.5	1	SL	Light Sag	1	25	25
17.6	18.6	1	FS	Severe Fracture	4	85	85
45	46.2	1.2	FM	Moderate Fracture	3	68	81.6
52.2	55	2.8	CM	Crack Moderate	2	37	103.6
66.3	67.8	1.5	CM	Crack Moderate	2	37	55.5
71	72.2	1.2	CS	Severe Crack	3	54	64.8

Table E.8. Case Number 2 COE Modified Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
72.5	74.4	1.9	FM	Moderate Fracture	3	68	129.2
77.5	78.5	1	SL	Light Sag	1	25	25
77.9	79	1.1	FM	Moderate Fracture	3	68	74.8
79.5	80	0.5	FS	Severe Fracture	4	85	42.5
98	99.1	1.1	FM	Moderate Fracture	3	68	74.8
110.3	111	0.7	CL	Light Crack	1	10	7
111	111.2	0.2	FL	Light Fracture	1	33	6.6
111	112.5	1.5	CM	Crack Moderate	2	37	55.5

Structural Condition Grading:

Total Score: 1013.8

Mean Score: 8.94

Peak Score: 85

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.3. Case Number 3

Pipe Length: 65.75 m

Sewer System: Combined

Pipe Diameter 200 mm

E.3.1. The PACP

Coding:

Table E.9. Case Number 3 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5		1	JOM	Joint Offset Medium	1
16.5	17	1	FS	Spiral Fracture	3

Table E.9. Case Number 3 PACP Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
17.2	17.8	1	D	Deformed	4
17.2	18.3	2	FL	Longitudinal Fracture	3
18.5	20.2	2	FL	Longitudinal Fracture	3
26.8	28	2	FL	Longitudinal Fracture	3
27.8	30	3	SRIC	Chemical Surface Damage, Roughness Increased	1
31.8	32.2	1	D	Deformed	4
32.4	34	2	FL	Longitudinal Fracture	3
35.7	36.2	1	FM	Multiple Fracture	4
40.4	41	1	FC	Circumferential Fracture	2
47.7	50	3	FL	Longitudinal Fracture	3
61.7	62.2	1	FS	Spiral Fracture	3
62.5	64	2	FL	Longitudinal Fracture	4
62.5		1	JOM	Joint Offset Medium	1
62.5	63	1	D	Deformed	4
65.5	65.75	1	SRIC	Chemical Surface Damage, Roughness Increased	1

Structural Condition Grading:

Segment Grade 1 Score: 6

Segment Grade 2 Score: 2

Segment Grade 3 Score: 39

Segment Grade 4 Score: 24

Structural Pipe Rating: 71

Structural Pipe Rating Index: 2.73 ≈ 3

E.3.2. The SRM4

Coding:

Table E.10. Case Number 3 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5		JDL	Joint Displaced Large	2
16.5	17	FS	Fracture Spiral	80
17.2	17.8	D (0-5%)	Deformed	20
17.2	18.3	FL	Fracture Longitudinal	40
18.5	20.2	FL	Fracture Longitudinal	40
26.8	28	FL	Fracture Longitudinal	40
27.8	30	SWS	Surface Wear Slight	5
31.8	32.2	D (5-10%)	Deformed	80
32.4	34	FL	Fracture Longitudinal	40
35.7	36.2	FM	Fracture Multiple	80
40.4	41	FC	Fracture Circumferential	40
47.7	50	FL	Fracture Longitudinal	40
61.7	62.2	FS	Fracture Spiral	80
62.5	64	FL	Fracture Longitudinal	40
62.5		JDL	Joint Displaced Large	2
62.5	63	D (0-5%)	Deformed	20
65.5	65.75	SWS	Surface Wear Slight	5

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.3.3. The COE Early Edition

Coding:

Table E.11. Case Number 3 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5		1	JM	Joint Displaced Moderate	3	3
16.5	17	0.5	FM	Fracture Moderate	4	2
17	18	1	SM	Sag Moderate	2	2
17.2	17.8	0.6	DM	Deformed Moderate	4	2.4
17.2	18.3	1.1	FM	Fracture Moderate	4	4.4

Table E.11. Case Number 3 COE Early Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
18.5	20.2	1.7	FM	Fracture Moderate	4	6.8
26.8	28	1.2	FM	Fracture Moderate	4	4.8
27.8	30	2.2	HL	Surface Damage Light	1	2.2
31.5	32.6	1.1	SM	Sag Moderate	2	2.2
31.8	32.2	0.4	DM	Deformed Moderate	4	1.6
32.4	34	1.6	FM	Fracture Moderate	4	6.4
35.7	36.2	0.5	FS	Fracture Severe	5	2.5
40.4	41	0.6	FL	Fracture Light	2	1.2
47.7	50	2.3	FM	Fracture Moderate	4	9.2
61.5	63	1.5	SM	Sag Moderate	2	3
61.7	62.2	0.5	FM	Fracture Moderate	4	2
62.5	64	1.5	FM	Fracture Moderate	4	6
62.5		1	JM	Joint Displaced Moderate	3	3
62.5	63	0.5	DM	Deformed Moderate	4	2
65.5	65.75	0.25	HL	Surface Damage Light	1	0.25

Structural Condition Grading:

Total Score: 66.95

Mean Score: 1.02

Peak Score: 5

Structural Condition Rating: 5

E.3.4. The COE Modified Edition

Coding:

Table E.12. Case Number 3 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5		1	JM	Moderate Displaced Joint	3	62	62
16.5	17	0.5	FM	Moderate Fracture	3	68	34
17	18	1	SL	Light Sag	1	25	25

Table E.12. Case Number 3 COE Modified Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
17.2	17.8	0.6	DM	Moderate Deformation	4	70	42
17.2	18.3	1.1	FM	Moderate Fracture	3	68	74.8
18.5	20.2	1.7	FM	Moderate Fracture	3	68	115.6
26.8	28	1.2	FM	Moderate Fracture	3	68	81.6
27.8	30	2.2	HL	Light Surface Damage	1	21	46.2
31.5	32.6	1.1	SL	Light Sag	1	25	27.5
31.8	32.2	0.4	DM	Moderate Deformation	4	70	28
32.4	34	1.6	FM	Moderate Fracture	3	68	108.8
35.7	36.2	0.5	FS	Severe Fracture	4	85	42.5
40.4	41	0.6	FL	Light Fracture	1	33	19.8
47.7	50	2.3	FM	Moderate Fracture	3	68	156.4
61.5	63	1.5	SL	Light Sag	1	25	37.5
61.7	62.2	0.5	FM	Moderate Fracture	3	68	34
62.5	64	1.5	FM	Moderate Fracture	3	68	102
62.5		1	JM	Moderate Displaced Joint	3	62	62
62.5	63	0.5	DM	Moderate Deformation	4	70	35
65.5	65.75	0.25	HL	Light Surface Damage	1	21	5.25

Structural Condition Grading:

Total Score: 1139.95

Mean Score: 17.34

Peak Score: 85

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.4. Case Number 4

Pipe Length: 37.68 m

Sewer System: Storm

Pipe Diameter 250 mm

E.4.1. The PACP

Coding:

Table E.13. Case Number 4 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
5.1	7.5	3	CL	Longitudinal Crack	2
6.1		1	BSV	Broken Soil Visible	5
6.2	6.9	1	D	Deformed	5
7.8	8.1	1	XP	Collapsed Pipe	5

Structural Condition Grading:

Segment Grade 2 Score: 6

Segment Grade 5 Score: 15

Structural Pipe Rating: 21

Structural Pipe Rating Index: 3.5 ≈ 3 or 4

E.4.2. The SRM4

Coding:

Table E.14. Case Number 4 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
5.1	7.5	CL	Crack Longitudinal	10
6.1		B	Broken	80
6.2	6.9	D	Deformed (16-20%)	165
7.8	8.1	XP	Collapsed	165

Structural Condition Grading:

Peak Score: 245

Computed Grade: 5

E.4.3. The COE Early Edition

Coding:

Table E.15. Case Number 4 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
5.1	7.5	2.4	CM	Crack Moderate	2	4.8
6.1		1	FX	Broken	5	5
6.2	6.9	0.7	DS	Deformed Severe	100	70
7.8	8.1	0.3	DX	Collapsed	115	34.5

Structural Condition Grading:

Total Score: 114.3

Mean Score: 3.03

Peak Score: 115

Structural Condition Rating: 5

E.4.4. The COE Modified Edition

Coding:

Table E.16. Case Number 4 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
5.1	7.5	2.4	CM	Moderate Crack	2	37	88.8
6.1		1	FXVL	Broken Pipe Light Void	5	100	100
6.2	6.9	0.7	DS	Severe Deformation	5	100	70
7.8	8.1	0.3	DX	Collapsed Pipe	5	100	30

Structural Condition Grading:

Total Score: 288.8

Mean Score: 7.66

Peak Score: 100

Multiple defect effect is not applicable

Structural Condition Rating: 5

E.5. Case Number 5

Pipe Length: 107.26 m

Sewer System: Combined

Pipe Diameter 250 mm

E.5.1. The PACP

Coding:

Table E.17. Case Number 5 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5	5.6	5	FL	Longitudinal Fracture	3
13	14	1	FM	Multiple Fracture	4
14.4	16	2	FS	Spiral Fracture	3
14.4	18.3	4	FL	Longitudinal Fracture	3
58.7	65	7	CL	Longitudinal Crack	2

Structural Condition Grading:

Segment Grade 2 Score: 14

Segment Grade 3 Score: 33

Segment Grade 4 Score: 4

Structural Pipe Rating: 51

Structural Pipe Rating Index: 2.7 ≈ 3

E.5.2. The SRM4

Coding:

Table E.18. Case Number 5 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	5.6	FL	Fracture Longitudinal	40
13	14	FM	Fracture Multiple	80
14.4	16	FS	Fracture Spiral	80
14.4	18.3	FL	Fracture Longitudinal	40
58.7	65	CL	Crack Longitudinal	10

Structural Condition Grading:

Peak Score: 120

Computed Grade: 4

E.5.3. The COE Early Edition

Coding:

Table E.19. Case Number 5 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	5.6	5	FM	Fracture Moderate	4	16.4
13	14	1	FS	Fracture Severe	5	5
14.4	16	2	FM	Fracture Moderate	4	8
14.4	18.3	4	FM	Fracture Moderate	4	15.6
58.7	65	7	CM	Crack Moderate	2	12.6

Structural Condition Grading:

Total Score: 57.6

Mean Score: 0.54

Peak Score: 5

Structural Condition Rating: 5

E.5.4. The COE Modified Edition

Coding:

Table E.20. Case Number 5 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	5.6	5	FM	Moderate Fracture	3	68	278.8
13	14	1	FS	Severe Fracture	4	85	85
14.4	16	2	FS	Severe Fracture	4	85	170
14.4	18.3	4	FM	Moderate Fracture	3	68	265.2
58.7	65	7	CM	Moderate Crack	2	37	233.1

Structural Condition Grading:

Total Score: 1032.1

Mean Score: 9.62

Peak Score: 85

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.6. Case Number 6

Pipe Length: 57.62 m

Sewer System: Combined

Pipe Diameter 250 mm

E.6.1. The PACP

Coding:

Table E.21. Case Number 6 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5	2	1	CC	Circumferential Crack	1

Table E.21. Case Number 6 PACP Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
36.4	39	3	FM	Multiple Fracture	4
36.4	37	1	CC	Circumferential Crack	1
48.6		1	JOM	Joint Offset Medium	1

Structural Condition Grading:

Segment Grade 1 Score: 3

Segment Grade 4 Score: 12

Structural Pipe Rating: 15

Structural Pipe Rating Index: 2.5 ≈ 2 or 3

E.6.2. The SRM4

Coding:

Table E.22. Case Number 6 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	2	CC	Crack Circumferential	10
36.4	39	FM	Fracture Multiple	80
36.4	37	CC	Crack Circumferential	10
48.6		JDL	Joint Displaced Large	2

Structural Condition Grading:

Peak Score: 90

Computed Grade: 4

E.6.3. The COE Early Edition

Coding:

Table E.23. Case Number 6 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	2	0.5	CL	Crack Light	1	1
36.4	39	2.6	FS	Fracture Severe	5	13
36.4	37	0.6	CL	Crack Light	1	1
48.6		1	JM	Joint Displacement Moderate	3	3

Structural Condition Grading:

Total Score: 18

Mean Score: 0.31

Peak Score: 5

Structural Condition Rating: 5

E.6.4. The COE Modified Edition

Coding:

Table E.24. Case Number 6 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	2	0.5	CL	Light Crack	1	10	5
36.4	39	2.6	FS	Severe Fracture	4	85	221
36.4	37	0.6	CL	Light Crack	1	10	6
48.6		1	JM	Moderate Displaced Joint	3	62	62

Structural Condition Grading:

Total Score: 294

Mean Score: 5.1

Peak Score: 85

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.7. Case Number 7

Pipe Length: 74.37 m

Sewer System: Combined

Pipe Diameter 200 mm

E.7.1. The PACP

Coding:

Table E.25. Case Number 7 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5	3.6	3	CM	Multiple Crack	3
15	15.4	1	CC	Circumferential Crack	1
41.9	56	15	CL	Longitudinal Crack	2
56.5	60.9	5	CL	Longitudinal Crack	2
60.8	62	2	FM	Multiple Crack	3
62	65	5	FL	Longitudinal Fracture	3
67	68	1	CL	Longitudinal Crack	2

Structural Condition Grading:

Segment Grade 1 Score: 1

Segment Grade 2 Score: 42

Segment Grade 3 Score: 30

Structural Pipe Rating: 73

Structural Pipe Rating Index: 2.3 ≈ 2

E.7.2. The SRM4

Coding:

Table E.26. Case Number 7 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	3.6	CM	Crack Multiple	40

Table E.26. Case Number 7 SRM4 Defect Coding, Cont'd

Dist	Dist_to	Code	Description	Unit Score
15	15.4	CC	Crack Circumferential	20
41.9	56	CL	Crack Longitudinal	20
56.5	60.9	CL	Crack Longitudinal	20
60.8	62	FM	Crack Multiple	40
62	65	FL	Fracture Longitudinal	40
67	68	CL	Crack Longitudinal	20

Structural Condition Grading:

Peak Score: 40

Computed Grade: 3

E.7.3. The COE Early Edition

Coding:

Table E.27. Case Number 7 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	3.6	2.1	CS	Crack Severe	4	8.4
15	15.4	0.4	CL	Crack Light	1	1
41.9	56	14.1	CM	Crack Moderate	2	28.2
56.5	60.9	4.4	CM	Crack Moderate	2	8.8
60.8	62	1.2	FS	Crack Severe	4	4.8
62	65	3	FM	Fracture Moderate	4	12
67	68	1	CM	Crack Moderate	2	2

Structural Condition Grading:

Total Score: 65.2

Mean Score: 0.88

Peak Score: 4

Structural Condition Rating: 4

E.7.4. The COE Modified Edition

Coding:

Table E.28. Case Number 7 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	3.6	2.1	CS	Severe Crack	3	54	113.4
15	15.4	0.4	CL	Light Crack	1	10	4
41.9	56	14.1	CM	Moderate Crack	2	37	521.7
56.5	60.9	4.4	CM	Moderate Crack	2	37	162.8
60.8	62	1.2	FS	Severe Crack	3	54	64.8
62	65	3	FM	Moderate Fracture	3	68	204
67	68	1	CM	Moderate Crack	2	37	37

Structural Condition Grading:

Total Score: 1107.7

Mean Score: 14.89

Peak Score: 68

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.8. Case Number 8

Pipe Length: 75 m

Sewer System: Combined

Pipe Diameter 200 mm

E.8.1. The PACP

Coding:

Table E.29. Case Number 8 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5	3.3	2	CM	Multiple Crack	3
12.6	15.8	4	CC	Circumferential Crack	1
31	46.2	16	CL	Longitudinal Crack	2
53	57.8	5	CL	Longitudinal Crack	2
60.5	62.1	2	FM	Multiple Crack	3
62.1	65.3	4	FL	Longitudinal Fracture	3
69	70.3	2	CL	Longitudinal Crack	2

Structural Condition Grading:

Segment Grade 1 Score: 4

Segment Grade 2 Score: 46

Segment Grade 3 Score: 24

Structural Pipe Rating: 74

Structural Pipe Rating Index: 2.1 ≈ 2

E.8.2. The SRM4

Coding:

Table E.30. Case Number 8 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	3.3	CM	Crack Multiple	40
12.6	15.8	CC	Crack Circumferential	20
31	46.2	CL	Crack Longitudinal	20
53	57.8	CL	Crack Longitudinal	20
60.5	62.1	FM	Crack Multiple	40
62.1	65.3	FL	Fracture Longitudinal	40
69	70.3	CL	Crack Longitudinal	20

Structural Condition Grading:

Peak Score: 40

Computed Grade: 3

E.8.3. The COE Early Edition

Coding:

Table E.31. Case Number 8 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	3.3	1.8	CS	Crack Severe	4	7.2
12.6	15.8	3.2	CL	Crack Light	1	3.2
31	46.2	15.2	CM	Crack Moderate	2	30.4
53	57.8	4.8	CM	Crack Moderate	2	8.8
60.5	62.1	1.6	FS	Crack Severe	4	6.4
62.1	65.3	3.2	FM	Fracture Moderate	4	12.8
69	70.3	1.3	CM	Crack Moderate	2	2.6

Structural Condition Grading:

Total Score: 71.4

Mean Score: 0.95

Peak Score: 4

Structural Condition Rating: 4

E.8.4. The COE Modified Edition

Coding:

Table E.32. Case Number 8 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	3.3	1.8	CS	Severe Crack	3	54	97.2
12.6	15.8	3.2	CL	Light Crack	1	10	32
31	46.2	15.2	CM	Moderate Crack	2	37	562.4
53	57.8	4.8	CM	Moderate Crack	2	37	177.6
60.5	62.1	1.6	FS	Severe Crack	3	54	86.4
62.1	65.3	3.2	FM	Moderate Fracture	3	68	217.6
69	70.3	1.3	CM	Moderate Crack	2	37	48.1

Structural Condition Grading:

Total Score: 1221.3

Mean Score: 16.28

Peak Score: 68

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.9. Case Number 9

Pipe Length: 109.7 m

Sewer System: Storm

Pipe Diameter 200 mm

E.9.1. The PACP

Coding:

Table E.33. Case Number 9 PACP Defect Coding

Dist	Dist_to	Code	Description	Defect Grade
10.7		JOM	Joint Offset Medium	1
12.6		JOM	Joint Offset Medium	1
16.6		JOM	Joint Offset Medium	1
24.3		JOM	Joint Offset Medium	1
25.6		JOM	Joint Offset Medium	1
28.2		JOM	Joint Offset Medium	1
32.6		JOM	Joint Offset Medium	1
34		JOM	Joint Offset Medium	1
39.6		JOM	Joint Offset Medium	1
41		JOM	Joint Offset Medium	1
41.7		JOM	Joint Offset Medium	1
47.1		JOM	Joint Offset Medium	1
87		JOM	Joint Offset Medium	1

Structural Condition Grading:

Segment Grade 1 Score: 13

Structural Pipe Rating: 13

Structural Pipe Rating Index: 1

E.9.2. The SRM4

Coding:

Table E.34. Case Number 9 SRM4 Defect Coding

Dist	**Dist_to**	**Code**	**Description**	**Unit Score**
10.7		JDL	Joint Displaced Large	2
12.6		JDL	Joint Displaced Large	2
16.6		JDL	Joint Displaced Large	2
24.3		JDL	Joint Displaced Large	2
25.6		JDL	Joint Displaced Large	2
28.2		JDL	Joint Displaced Large	2
32.6		JDL	Joint Displaced Large	2
34		JDL	Joint Displaced Large	2
39.6		JDL	Joint Displaced Large	2
41		JDL	Joint Displaced Large	2
41.7		JDL	Joint Displaced Large	2
47.1		JDL	Joint Displaced Large	2
87		JDL	Joint Displaced Large	2

Structural Condition Grading:

Peak Score: 2

Computed Grade: 2

E.9.3. The COE Early Edition

Coding:

Table E.35. Case Number 9 COE Early Edition Defect Coding

Dist	Dist_to	Code	Description	Unit Score
10.7		JM	Joint Displacement Moderate	3
12.6		JM	Joint Displacement Moderate	3
16.6		JM	Joint Displacement Moderate	3
24.3		JM	Joint Displacement Moderate	3
25.6		JM	Joint Displacement Moderate	3
28.2		JM	Joint Displacement Moderate	3
32.6		JM	Joint Displacement Moderate	3
34		JM	Joint Displacement Moderate	3
39.6		JM	Joint Displacement Moderate	3
41		JM	Joint Displacement Moderate	3
41.7		JM	Joint Displacement Moderate	3
47.1		JM	Joint Displacement Moderate	3
87		JM	Joint Displacement Moderate	3

Structural Condition Grading:

Total Score: 39

Mean Score: 0.36

Peak Score: 3

Structural Condition Rating: 3

E.9.4. The COE Modified Edition

Coding:

Table E.36. Case Number 9 COE Modified Edition Defect Coding

Dist	Dist_to	Code	Description	Rating	Defect Weight
10.7		JM	Moderate Displaced Joint	3	62
12.6		JM	Moderate Displaced Joint	3	62
16.6		JM	Moderate Displaced Joint	3	62
24.3		JM	Moderate Displaced Joint	3	62
25.6		JM	Moderate Displaced Joint	3	62
28.2		JM	Moderate Displaced Joint	3	62

Table E.36. Case Number 9 COE Modified Edition Defect Coding, Cont'd

Dist	Dist_to	Code	Description	Rating	Defect Weight
32.6		JM	Moderate Displaced Joint	3	62
34		JM	Moderate Displaced Joint	3	62
39.6		JM	Moderate Displaced Joint	3	62
41		JM	Moderate Displaced Joint	3	62
41.7		JM	Moderate Displaced Joint	3	62
47.1		JM	Moderate Displaced Joint	3	62
87		JM	Moderate Displaced Joint	3	62

Structural Condition Grading:

Total Score: 806

Mean Score: 7.35

Peak Score: 62

Multiple defect effect is not applicable

Structural Condition Rating: 3

E.10. Case Number 10

Pipe Length: 109.7 m

Sewer System: Storm

Pipe Diameter 200 mm

Note: Case number 10, is a newer survey of case number 9.

E.10.1. The PACP

Coding:

Table E.37. Case Number 10 PACP Defect Coding

Dist	Dist_to	Code	Description	Defect Grade
10.7		JOM	Joint Offset Medium	1
12.6		JOM	Joint Offset Medium	1

Table E.37. Case Number 10 PACP Defect Coding, Cont'd

Dist	Dist_to	Code	Description	Defect Grade
16.6		JOM	Joint Offset Medium	1
24.3		JOM	Joint Offset Medium	1
25.6		JOM	Joint Offset Medium	1
28.2		JOM	Joint Offset Medium	1
32.6		JOM	Joint Offset Medium	1
34		JOM	Joint Offset Medium	1
39.6		JOM	Joint Offset Medium	1
41		JOM	Joint Offset Medium	1
41.7		JOM	Joint Offset Medium	1
47.1		JOM	Joint Offset Medium	1
87		JOM	Joint Offset Medium	1
93.2		HVV	Hole, Void Visible	5

Structural Condition Grading:

Segment Grade 1 Score: 13

Segment Grade 5 Score: 5

Structural Pipe Rating: 18

Structural Pipe Rating Index: 1.3 ≈ 1

E.10.2. The SRM4

Coding:

Table E.38. Case Number 10 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
10.7		JDL	Joint Displaced Large	2
12.6		JDL	Joint Displaced Large	2
16.6		JDL	Joint Displaced Large	2
24.3		JDL	Joint Displaced Large	2
25.6		JDL	Joint Displaced Large	2
28.2		JDL	Joint Displaced Large	2
32.6		JDL	Joint Displaced Large	2
34		JDL	Joint Displaced Large	2

Table E.38. Case Number 10 SRM4 Defect Coding, Cont'd

Dist	Dist_to	Code	Description	Unit Score
39.6		JDL	Joint Displaced Large	2
41		JDL	Joint Displaced Large	2
41.7		JDL	Joint Displaced Large	2
47.1		JDL	Joint Displaced Large	2
87		JDL	Joint Displaced Large	2
93.2		H	Hole (Redial Extent > 1/4)	165

Structural Condition Grading:

Peak Score: 165

Computed Grade: 5

E.10.3. The COE Early Edition

Coding:

Table E.39. Case Number 10 COE Early Edition Defect Coding

Dist	Dist_to	Code	Description	Unit Score
10.7		JM	Joint Displacement Moderate	3
12.6		JM	Joint Displacement Moderate	3
16.6		JM	Joint Displacement Moderate	3
24.3		JM	Joint Displacement Moderate	3
25.6		JM	Joint Displacement Moderate	3
28.2		JM	Joint Displacement Moderate	3
32.6		JM	Joint Displacement Moderate	3
34		JM	Joint Displacement Moderate	3
39.6		JM	Joint Displacement Moderate	3
41		JM	Joint Displacement Moderate	3
41.7		JM	Joint Displacement Moderate	3
47.1		JM	Joint Displacement Moderate	3
87		JM	Joint Displacement Moderate	3
93.2		FX	Broken pipe	100

Structural Condition Grading:

Total Score: 44

Mean Score: 0.4

Peak Score: 100

Structural Condition Rating: 5

E.10.4. The COE Modified Edition

Coding:

Table E.40. Case Number 10 COE Modified Edition Defect Coding

Dist	Dist_to	Code	Description	Rating	Unit Weight
10.7		JM	Moderate Displaced Joint	3	62
12.6		JM	Moderate Displaced Joint	3	62
16.6		JM	Moderate Displaced Joint	3	62
24.3		JM	Moderate Displaced Joint	3	62
25.6		JM	Moderate Displaced Joint	3	62
28.2		JM	Moderate Displaced Joint	3	62
32.6		JM	Moderate Displaced Joint	3	62
34		JM	Moderate Displaced Joint	3	62
39.6		JM	Moderate Displaced Joint	3	62
41		JM	Moderate Displaced Joint	3	62
41.7		JM	Moderate Displaced Joint	3	62
47.1		JM	Moderate Displaced Joint	3	62
87		JM	Moderate Displaced Joint	3	62
93.2		FXVS	Severe Void Broken Pipe	5	100

Structural Condition Grading:

Total Score: 906

Mean Score: 8.26

Peak Score: 100

Multiple defect effect is not applicable

Structural Condition Rating: 5

E.11. Case Number 11

Pipe Length: 40 m

Sewer System: Storm

Pipe Diameter 200 mm

E.11.1. The PACP

Coding:

Table E.41. Case Number 11 PACP Defect Coding

Dist	Dist_to	Code	Description	Defect Grade
39		HVV	Hole, Void Visible	5

Structural Condition Grading:

Segment Grade 5 Score: 5

Structural Pipe Rating: 5

Structural Pipe Rating Index: 5

E.11.2. The SRM4

Coding:

Table E.42. Case Number 11 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
39		H	Hole (Redial Extent <1/4)	80

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.11.3. The COE Early Edition

Coding:

Table E.43. Case Number 11 COE Early Edition Defect Coding

Dist	Dist_to	Code	Description	Unit Score
39		FX	Broken Pipe	110

Structural Condition Grading:

Total Score: 110

Mean Score: 2.75

Peak Score: 110

Structural Condition Rating: 5

E.11.4. The COE Modified Edition

Coding:

Table E.44. Case Number 11 COE Modified Edition Defect Coding

Dist	Dist_to	Code	Description	Unit Score	Unit Weight
39		FXVS	Severe Void Broken Pipe	5	100

Structural Condition Grading:

Total Score: 100

Mean Score: 2.5

Peak Score: 100

Multiple defect effect is not applicable

Structural Condition Rating: 5

E.12. Case Number 12

Pipe Length: 90.6 m

Sewer System: Sanitary

Pipe Diameter 250 mm

E.12.1. The PACP

Coding:

Table E.45. Case Number 12 PACP Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Defect Grade**
1.7		1	JOM	Joint Offset Medium	1
22.8	25	3	FL	Longitudinal Fracture	3
23		1	HVV	Hole, Void Visible	5

Structural Condition Grading:

Segment Grade 1 Score: 1

Segment Grade 3 Score: 9

Segment Grade 5 Score: 5

Structural Pipe Rating: 15

Structural Pipe Rating Index: 3

E.12.2. The SRM4

Coding:

Table E.46. Case Number 12 SRM4 Defect Coding

Dist	**Dist_to**	**Code**	**Description**	**Unit Score**
1.7		JDL	Joint Displaced Large	2
22.8	25	FL	Fracture Longitudinal	40
23		H	Hole (Redial Extent <1/4)	80

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.12.3. The COE Early Edition

Coding:

Table E.47. Case Number 12 COE Early Edition Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Unit Score**	**Defect Score**
1.7		1	JM	Joint Displacement Moderate	3	3
22.8	25	2.2	FM	Fracture Moderate	4	8.8
23		1	FX	Broken Pipe	110	110

Structural Condition Grading:

Total Score: 138.8

Mean Score: 1.53

Peak Score: 110

Structural Condition Rating: 5

E.12.4. The COE Modified Edition

Coding:

Table E.48. Case Number 12 COE Modified Edition Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Rating**	**Unit Weight**	**Defect Weight**
1.7		1	JM	Moderate Displaced joint	3	62	62
22.8	25	2.2	FM	Moderate Fracture	3	68	149.6
23		1	FXVS	Severe Void Broken Pipe	5	100	100

Structural Condition Grading:

Total Score: 311.6

Mean Score: 3.44

Peak Score: 100

Multiple defect effect is not applicable

Structural Condition Rating: 5

E.13. Case Number 13

Pipe Length: 90.6 m

Sewer System: Sanitary

Pipe Diameter 250 mm

Note: Case number 13 is a newer survey of case number 12 in which the hole at distance 23 m has become larger.

E.13.1. The PACP

Coding:

Table E.49. Case Number 13 PACP Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Defect Grade**
1.7		1	JOM	Joint Offset Medium	1
22.8	25	3	FL	Longitudinal Fracture	3
23		1	HVV	Hole, Void Visible	5

Structural Condition Grading:

Segment Grade 1 Score: 1

Segment Grade 3 Score: 9

Segment Grade 5 Score: 5

Structural Pipe Rating: 15

Structural Pipe Rating Index: 3

E.13.2. The SRM4

Coding:

Table E.50. Case Number 13 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.7		JDL	Joint Displaced Large	2
22.8	25	FL	Fracture Longitudinal	40
23		H	Hole (Redial Extent >1/4)	165

Structural Condition Grading:

Peak Score: 165

Computed Grade: 5

E.13.3. The COE Early Edition

Coding:

Table E.51. Case Number 13 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.7		1	JM	Joint Displacement Moderate	3	3
22.8	25	2.2	FM	Fracture Moderate	4	8.8
23		1	FX	Broken Pipe	110	110

Structural Condition Grading:

Total Score: 138.8

Mean Score: 1.53

Peak Score: 110

Structural Condition Rating: 5

E.13.4. The COE Modified Edition

Coding:

Table E.52. Case Number 13 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.7		1	JM	Moderate Displaced joint	3	62	62
22.8	25	2.2	FM	Moderate Fracture	3	68	149.6
23		1	FXVS	Severe Void Broken Pipe	5	100	100

Structural Condition Grading:

Total Score: 311.6

Mean Score: 3.44

Peak Score: 100

Multiple defect effect is not applicable

Structural Condition Rating: 5

E.14. Case Number 14

Pipe Length: 73.3 m

Sewer System: Sanitary

Pipe Diameter 375 mm

E.14.1. The PACP

Coding:

Table E.53. Case Number 14 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Grade
1.5	1.7	1	FM	Multiple Fracture	4
1.7	4	3	FL	Longitudinal Fracture	3
5.4	5.8	1	D	Deformed	4

Table E.53. Case Number 14 PACP Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Grade
5.4	6.3	1	FL	Longitudinal Fracture	3
6.5		1	HSV	Hole, Soil Visible	5
10	13.2	4	FL	Longitudinal Fracture	3
14	37	23	FL	Longitudinal Fracture	3
34	35	1	FC	Circumferential Fracture	2
41	44	3	CL	Longitudinal Crack	2
44	50	6	FL	Longitudinal Fracture	3
48.2	49	1	D	Deformed	4
64.8	65	1	D	Deformed	4
66		1	BSV	Broken, Soil Visible	5
66.1		1	HVV	Hole, Void Visible	5
71	71.8	1	FM	Multiple Fracture	4

Structural Condition Grading:

Segment Grade 2 Score: 8

Segment Grade 3 Score: 111

Segment Grade 4 Score: 20

Segment Grade 5 Score: 15

Structural Pipe Rating: 154

Structural Pipe Rating Index: 3.14 ≈ 3

E.14.2. The SRM4

Coding:

Table E.54. Case Number 14 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	1.7	FM	Fracture Multiple	80
1.7	4	FL	Fracture Longitudinal	40
5.4	5.8	D	Deformed (0-5%)	20
5.4	6.3	FL	Fracture Longitudinal	40

Table E.54. Case Number 14 SRM4 Defect Coding, Cont'd

Dist	Dist_to	Code	Description	Unit Score
6.5		H	Hole (Redial Extent <1/4)	80
10	13.2	FL	Fracture Longitudinal	40
14	37	FL	Fracture Longitudinal	40
34	35	FC	Fracture Circumferential	40
41	44	CL	Crack Longitudinal	10
44	50	FL	Fracture Longitudinal	40
48.2	49	D	Deformed (0-5%)	20
64.8	65	D	Deformed (0-5%)	20
66		B	Broken	80
66.1		H	Hole (Radial Extent >1/4)	165
71	71.8	FM	Fracture Multiple	80

Structural Condition Grading:

Peak Score: 245

Computed Grade: 5

E.14.3. The COE Early Edition

Coding:

Table E.55. Case Number 14 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	1.7	0.2	FS	Fracture Severe	5	1
1.7	4	2.3	FM	Fracture Moderate	4	9.2
5.4	6	0.6	SM	Sag Moderate	2	1.2
5.4	5.8	0.4	DM	Deformed Moderate	4	1.6
5.4	6.3	0.9	FM	Fracture Moderate	4	3.6
6.5		1	FX	Broken Pipe	5	5
10	13.2	3.2	FM	Fracture Moderate	4	12.8
14	37	23	FM	Fracture Moderate	4	92
34	35	1	FL	Fracture Light	2	2
41	44	3	CM	Crack Moderate	2	6
44	46	2	SM	Sag Moderate	2	4
44	50	6	FM	Fracture Moderate	4	24
48.2	49	0.8	DM	Deformed Moderate	4	3.2

Table E.55. Case Number 14 COE Early Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
64.8	65	0.2	DM	Deformed Moderate	4	0.8
66		1	FX	Broken Pipe	110	110
71	71.8	0.8	FS	Fracture Severe	5	4

Structural Condition Grading:

Total Score: 280.4

Mean Score: 3.82

Peak Score: 110

Structural Condition Rating: 5

E.14.4. The COE Modified Edition

Coding:

Table E.56. Case Number 14 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	1.7	0.2	FS	Severe Fracture	4	85	17
1.7	4	2.3	FM	Moderate Fracture	3	68	156.4
5.4	6	0.6	SL	Light Sag	1	25	15
5.4	5.8	0.4	DM	Moderate Deformed	4	70	28
5.4	6.3	0.9	FM	Moderate Fracture	4	68	61.2
6.5		1	FXVL	Light Void Broken Pipe	5	86	86
10	13.2	3.2	FM	Moderate Fracture	3	68	217.6
14	37	23	FM	Moderate Fracture	3	68	1564
34	35	1	FL	Light Fracture	1	33	33
41	44	3	CM	Moderate Crack	2	37	111
44	46	2	SL	Light Sag	1	25	50
44	50	6	FM	Moderate Fracture	3	68	408
48.2	49	0.8	DM	Moderate Deformed	4	70	56
64.8	65	0.2	DM	Moderate Deformed	4	70	14
66		1	FXM	No Void Broken Pipe	4	73	73
66.1		1	FXVS	Severe Void Broken Pipe	5	100	100
71	71.8	0.8	FS	Severe Fracture	4	85	68

Structural Condition Grading:

Total Score: 3058.2

Mean Score: 41.72

Peak Score: 100

Multiple defect effect is not applicable

Structural Condition Rating: 5

E.15. Case Number 15

Pipe Length: 40 m

Sewer System: Storm

Pipe Diameter 250 mm

E.15.1. The PACP

Coding:

Table E.57. Case Number 15 PACP Defect Coding

Dist	Dist_to	Code	Description	Defect Grade
38		JSL	Joint Separated Large	2

Structural Condition Grading:

Segment Grade 2 Score: 2

Structural Pipe Rating: 2

Structural Pipe Rating Index: 2

E.15.2. The SRM4

Coding:

Table E.58. Case Number 15 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
38		OJSV	Open Joint Soil Visible	165

Structural Condition Grading:

Peak Score: 165

Computed Grade: 5

E.15.3. The COE Early Edition

Coding:

Table E.59. Case Number 15 COE Early Edition Defect Coding

Dist	Dist_to	Code	Description	Unit Score
38		OS	Open Joint Severe	5

Structural Condition Grading:

Total Score: 5

Mean Score: 0.125

Peak Score: 5

Structural Condition Rating: 5

E.15.4. The COE Modified Edition

Coding:

Table E.60. Case Number 15 COE Modified Edition Defect Coding

Dist	Dist_to	Code	Description	Rating	Unit Weight
38		OS	Severe Open Joint	4	72

Structural Condition Grading:

Total Score: 72

Mean Score: 1.8

Peak Score: 72

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.16. Case Number 16

Pipe Length: 33.2 m

Sewer System: Sanitary

Pipe Diameter 200 mm

E.16.1. The PACP

Coding:

Table E.61. Case Number 16 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
1.5	1.7	1	CL	Longitudinal Crack	2
1.5	1.7	1	FC	Circumferential Fracture	2
1.6		1	JSM	Joint Offset Medium	1
6.3	6.5	1	CL	Longitudinal Crack	2
9.9	10	1	FS	Fracture Spiral	3
19.6		1	JSM	Joint Offset Medium	1
25.2	25.5	1	FS	Fracture Spiral	3
26.4	26.5	1	FC	Circumferential Fracture	2
29.3	30.2	1	CS	Crack Spiral	2
30.5	30.8	1	CL	Longitudinal Crack	2
30.8	30.9	1	FC	Circumferential Fracture	2

Structural Condition Grading:

Segment Grade 1 Score: 2

Segment Grade 2 Score: 14

Segment Grade 3 Score: 6

Structural Pipe Rating: 22

Structural Pipe Rating Index: 2

E.16.2. The SRM4

Coding:

Table E.62. Case Number 16 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	1.7	CL	Crack Longitudinal	10
1.5	1.7	FC	Fracture Circumferential	40
1.6		JDM	Joint Displaced Medium	1
6.3	6.5	CL	Crack Longitudinal	10
9.9	10	FS	Fracture Spiral	80
19.6		JDM	Joint Displaced Medium	1
25.2	25.5	FS	Fracture Spiral	80
26.4	26.5	FC	Fracture Circumferential	40
29.3	30.2	CS	Crack Spiral	40
30.5	30.8	CL	Crack Longitudinal	10
30.8	30.9	FC	Fracture Circumferential	40

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.16.3. The COE Early Edition

Coding:

Table E.63. Case Number 16 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	1.7	0.2	CM	Crack moderate	2	0.4
1.5	1.7	0.2	FL	Fracture Light	2	0.4

Table E.63. Case Number 16 COE Early Edition Defect Coding, Cont'd

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.6		1	JL	Joint Displacement Light	2	2
6.3	6.5	0.2	CM	Crack moderate	2	0.4
9.9	10	0.1	FL	Fracture Light	2	0.2
19.6		1	JL	Joint Displacement Light	2	2
25.2	25.5	0.3	FL	Fracture Light	2	0.6
26.4	26.5	0.1	FL	Fracture Light	2	0.2
29.3	30.2	0.9	CL	Crack Light	1	0.9
30.5	30.8	0.3	CM	Crack moderate	2	0.6
30.8	30.9	0.1	FL	Fracture Light	2	0.2

Structural Condition Grading:

Total Score: 7.9

Mean Score: 0.24

Peak Score: 2

Structural Condition Rating: 2

E.16.4. The COE Modified Edition

Coding:

Table E.64. Case Number 16 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	1.7	0.2	CM	Moderate Crack	2	37	7.4
1.5	1.7	0.2	FL	Light Fracture	1	33	6.6
1.6		1	JL	Light Displaced Joint	1	28	28
6.3	6.5	0.2	CM	Moderate Crack	2	37	7.4
9.9	10	0.1	FL	Light Fracture	1	33	3.3
19.6		1	JL	Light Displaced Joint	1	28	28
25.2	25.5	0.3	FL	Light Fracture	1	33	9.9
26.4	26.5	0.1	FL	Light Fracture	1	33	3.3
29.3	30.2	0.9	CL	Light Crack	1	10	9
30.5	30.8	0.3	CM	Moderate Crack	2	37	11.1
30.8	30.9	0.1	FL	Light Fracture	1	33	3.3

Structural Condition Grading:

Total Score: 117.3

Mean Score: 3.53

Peak Score: 37

Multiple defect effect is not applicable

Structural Condition Rating: 2

E.17. Case Number 17

Pipe Length: 49. 3 m

Sewer System: Sanitary

Pipe Diameter 200 mm

E.17.1. The PACP

Coding:

Table E.65. Case Number 17 PACP Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Defect Grade**
1.5	1.7	1	FS	Fracture Spiral	3
5	5.2	1	FC	Circumferential Fracture	2
14.6		1	JSM	Joint Open Medium	1
20.1	21.5	2	FL	Longitudinal Fracture	3
32	33.4	2	FS	Fracture Spiral	3
34		1	JSM	Joint Offset Medium	1
40	41	1	FS	Fracture Spiral	3

Structural Condition Grading:

Segment Grade 1 Score: 2

Segment Grade 2 Score: 14

Segment Grade 3 Score: 6

Structural Pipe Rating: 22

Structural Pipe Rating Index: 2

E.17.2. The SRM4

Coding:

Table E.66. Case Number 17 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
1.5	1.7	FS	Fracture Spiral	80
5	5.2	FC	Fracture Circumferential	40
14.6		JDM	Joint Displaced Medium	1
20.1	21.5	FL	Fracture Longitudinal	40
32	33.4	FS	Fracture Spiral	80
34		JDM	Joint Displaced Medium	1
40	41	FS	Fracture Spiral	80

Structural Condition Grading:

Peak Score: 80

Computed Grade: 4

E.17.3. The COE Early Edition

Coding:

Table E.67. Case Number 17 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	1.7	0.2	FM	Fracture Moderate	4	0.8
5	5.2	0.2	FL	Fracture Light	2	0.4
14.6		1	JL	Joint Displacement Light	2	2
20.1	21.5	1.4	FM	Fracture Moderate	4	5.6
32	33.4	1.4	FM	Fracture Moderate	4	5.6
34		1	JL	Joint Displacement Light	2	2
40	41	1	FM	Fracture Moderate	4	4

Structural Condition Grading:

Total Score: 20.4

Mean Score: 0.41

Peak Score: 4

Structural Condition Rating: 4

E.17.4. The COE Modified Edition

Coding:

Table E.68. Case Number 17 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	1.7	0.2	FM	Moderate Fracture	3	68	13.6
5	5.2	0.2	FL	Light Fracture	1	33	6.6
14.6		1	JL	Light Displaced Joint	1	28	28
20.1	21.5	1.4	FM	Moderate Fracture	3	68	95.2
32	33.4	1.4	FM	Moderate Fracture	3	68	95.2
34		1	JL	Light Displaced Joint	1	28	28
40	41	1	FM	Moderate Fracture	3	68	68

Structural Condition Grading:

Total Score: 334.6

Mean Score: 6.79

Peak Score: 68

Multiple defect effect is not applicable

Structural Condition Rating: 3

E.18. Case Number 18

Pipe Length: 39 m

Sewer System: Sanitary

Pipe Diameter 200 mm

E.18.1. The PACP

Coding:

Table E.69. Case Number 18 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Grade
5.7	10.3	5	SAP	Aggregate Projecting	3

Structural Condition Grading:

Segment Grade 3 Score: 15

Structural Pipe Rating: 15

Structural Pipe Rating Index: 3

E.18.2. The SRM4

Coding:

Table E.70. Case Number 18 SRM4 Defect Coding

Dist	Dist_to	Code	Description	Unit Score
5.7	10.3	SWM	Surface Wear Medium	20

Structural Condition Grading:

Peak Score: 20

Computed Grade: 2

E.18.3. The COE Early Edition

Coding:

Table E.71. Case Number 18 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.8	5.7	3.9	SL	Sag Light	1	3.9
5.7	10.3	4.6	HM	Surface Wear Moderate	2	9.2
15.6	18.6	3	SL	Sag Light	1	3
19.4	21.3	1.9	SL	Sag Light	2	3.8
25.8	34	8.2	SL	Sag Light	3	24.6

Structural Condition Grading:

Total Score: 44.5

Mean Score: 1.14

Peak Score: 3

Structural Condition Rating: 3

E.18.4. The COE Modified Edition

Coding:

Table E.72. Case Number 18 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.8	5.7	3.9	SL	Sag light	1	25	97.5
5.7	10.3	4.6	HM	Moderate Surface Damage	3	53	243.8
15.6	18.6	3	SL	Sag light	1	25	75
19.4	21.3	1.9	SL	Sag light	1	25	47.5
25.8	34	8.2	SL	Sag light	1	25	205

Structural Condition Grading:

Total Score: 668.8

Mean Score: 17.15

Peak Score: 53

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.19. Case Number 19

Pipe Length: 36.23 m

Sewer System: Sanitary

Pipe Diameter 200 mm

E.19.1. The PACP

Coding:

Table E.73. Case Number 19 PACP Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Defect Score**
1.5	17.5	16	SAP	Aggregate Projecting	3
20.5	27	7	SRIC	Chemical Surface Damage, Roughness Increased	1

Structural Condition Grading:

Segment Grade 1 Score: 7

Segment Grade 3 Score: 48

Structural Pipe Rating: 55

Structural Pipe Rating Index: 2.39 ≈ 2

E.19.2. The SRM4

Coding:

Table E.74. Case Number 19 SRM4 Defect Coding

Dist	**Dist_to**	**Defect Count**	**Code**	**Description**	**Defect Score**
1.5	17.5	16	SWM	Surface Wear Medium	20
20.5	27	6.5	SWS	Surface Wear Slight	5

Structural Condition Grading:

Peak Score: 20

Computed Grade: 2

E.19.3. The COE Early Edition

Coding:

Table E.75. Case Number 19 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	17.5	16	HM	Surface Wear Moderate	2	32
20.5	27	6.5	HL	Surface Damage Light	1	6.5

Structural Condition Grading:

Total Score: 38.5

Mean Score: 1.06

Peak Score: 2

Structural Condition Rating: 2

E.19.4. The COE Modified Edition

Coding:

Table E.76. Case Number 19 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	17.5	16	HM	Moderate Surface Damage	3	53	848
20.5	27	6.5	HL	Light Surface Damage	1	21	136.5

Structural Condition Grading:

Total Score: 984.5

Mean Score: 27.17

Peak Score: 53

Multiple defect effect is not applicable

Structural Condition Rating: 4

E.20. Case Number 20

Pipe Length: 30 m

Sewer System: Combined

Pipe Diameter 250 mm

E.20.1. The PACP

Coding:

Table E.77. Case Number 20 PACP Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Score
1.5	28	27	SAP	Aggregate Projecting	3

Structural Condition Grading:

Segment Grade 3 Score: 81

Structural Pipe Rating: 81

Structural Pipe Rating Index: 3

E.20.2. The SRM4

Coding:

Table E.78. Case Number 20 SRM4 Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Defect Score
1.5	28	26.5	SWM	Surface Wear Medium	20

Structural Condition Grading:

Peak Score: 20

Computed Grade: 2

E.20.3. The COE Early Edition

Coding:

Table E.79. Case Number 20 COE Early Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Unit Score	Defect Score
1.5	28	16	HM	Surface Wear Moderate	2	32

Structural Condition Grading:

Total Score: 53

Mean Score: 1.77

Peak Score: 2

Structural Condition Rating: 2

E.80.4. The COE Modified Edition

Coding:

Table E.80. Case Number 20 COE Modified Edition Defect Coding

Dist	Dist_to	Defect Count	Code	Description	Rating	Unit Weight	Defect Weight
1.5	28	26.5	HM	Moderate Surface Damage	3	53	848

Structural Condition Grading:

Total Score: 1404.5

Mean Score: 46.82

Peak Score: 53

Defective Length Percentage: 88.3

Table 2.7: Defective length more than 80% → SR: 5

Structural Condition Rating: 5