Rethinking Collection System Cleaning Using Acoustic Inspection

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ABSTRACT

Setting up a utility's preventative maintenance program for their gravity-fed collection system's cleaning involves recognizing that many pipe segments scheduled for cleaning will not need it. But, this cost of over cleaning must be balanced against insufficient maintenance resulting in excessive overflows. We present herein a new diagnostic tool, the Sewer Line – Rapid Assessment Tool or SL-RAT™. The SL-RAT is an onsite inspection device developed by InfoSense with the support of Charlotte-Mecklenburg Utilities (CMU). The SL-RAT diagnostic capability allows cleaning requirements for pipe segments to be economically prioritized prior to conducting cleaning operations. We show that significant cost savings can be achieved through: reduced asset condition assessment costs, reduced cleaning-related overflows, and reduced non-value added cleaning effort. In this paper, CMU Case Studies are reviewed and used to show how the SL-RAT acoustic inspection system can be used to establish a Sewer Line Condition Based Maintenance (SL-CBM™) program.

KEYWORDS

Sewer line inspection, wastewater operation management, pipe blockage assessment, collection system cleaning, condition based maintenance, acoustic pipe inspection.

INTRODUCTION

Based on Charlotte Mecklenburg Utilities' (CMU) ongoing efforts to enhance their gravity-fed collection system's maintenance operations, it has been recognized that 50% or more of pipe segments cleaned receive little to no benefit as they were essentially already clean prior to maintenance. This insight is further compounded by the fact that locations chosen for conducting cleaning operations were identified using spatial analysis as well as historical performance and institutional system knowledge as inputs. Collection system maintenance requires allocating cleaning resources to the right place prior to system failure (SSO, mainline blockages and building backups). CMU's overall overflow rate has been between 8 and 9 overflows/100 miles/year with over 20% of the system cleaned annually. For comparison, a scatter plot of overflows/100 miles vs. percentage system cleaned is depicted in Figure 1. The plot is based on self reporting from sixteen municipalities' annual performance reports. As would be anticipated, linear regression indicates a strong correlation between cleaning effort and overflow reduction. Due to the inherent random nature of the underlying mechanisms that build up to overflows, there is likely a diminishing return with more cleaning. Therefore, as the percentage of the system cleaned increases, an even larger proportion of wasteful and unnecessary cleaning will be conducted, unless, an improved method for targeting cleaning operations can be implemented.

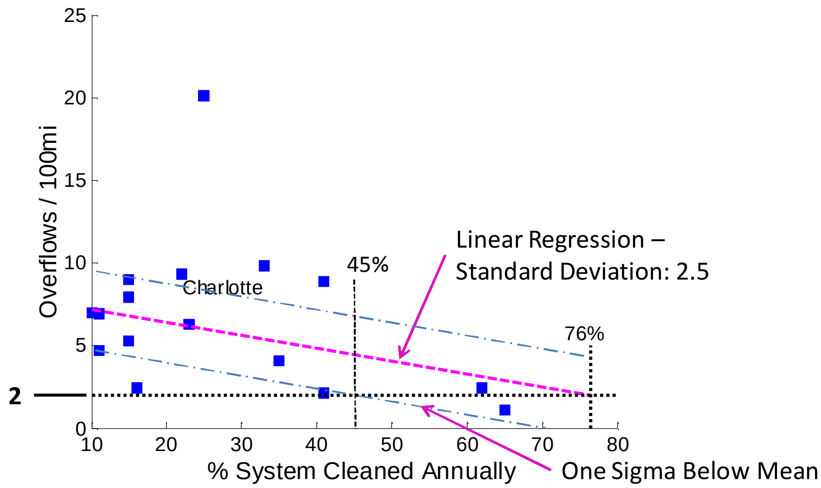


Figure 1 Comparison of sixteen municipalities' performance in maintaining their collection system's overflow rates based on the percentage of the system cleaned annually.

Historically, using condition based inspection to determine where and when to deploy collection system cleaning resources has not been economically feasible. Existing pipe inspection methods are either too cost prohibitive for wide spread use or provide inadequate condition assessment. The Sewer Line – Rapid Assessment Tool or SL-RAT™ is a new diagnostic tool specifically designed to address the need for identifying pipe blockage in support of an overall collection system maintenance program. The SL-RAT is an onsite inspection device developed by InfoSense with the support of CMU. The SL-RAT diagnostic capability allows cleaning requirements for pipe segments to be economically prioritized prior to conducting cleaning operations. The acoustic testing equipment provides a clear condition assessment directly correlated with cleaning requirements. The acoustic inspection operation requires significantly less resources than is required for current maintenance practices. This provides the opportunity to rethink using condition based maintenance as a viable tool for deploying cleaning resources. This novel approach can both improve maintenance quality and reduce unnecessary maintenance operations.

Over the past two years, CMU has conducted well over three thousand SL-RAT acoustic inspections of pipe segments. This has provided a condition assessment for over 850 thousand feet of their collection system. In the past year, the focus of inspections has changed from evaluating the SL-RAT technology, to incorporating the technology as the enabler for a newly evolving collection system cleaning CBM program based on acoustic inspections. The objective of the paper is to provide:

1. Direct evaluation of the SL-RAT as a condition based assessment tool. This evaluation is based on a pilot project conducted by CMU to evaluate the SL-RAT's effectiveness in prioritizing maintenance operations, as well as to evaluate its cost effectiveness and ease of operation. This study involved a systemic comparison between acoustic inspection and corresponding CCTV assessment both before and after maintenance operations.
2. Direct evaluation of integrating the SL-RAT for condition based assessment. An illustrative case study is presented to examine the procedural and operational advantage

for using the SL-RAT as a conditional based assessment tool for a consolidated cleaning project.

3. Evaluate the capability and requirements for developing a Sewer Line Condition Based Maintenance (SL-CBM™) program based on SL-RAT acoustic inspections. Examine the trade-offs in developing a SL-CBM program to achieve a collection system performance goal of 2 overflows/100 miles/year without increasing the current operations cost for cleaning.
4. Evaluate the Cost versus Performance for an SL-CBM using the SL-RAT based on the spatial and temporal overflow patterns within the CMU collection system. This evaluation is based on an analytical model which incorporates the CMU overflow data for the past thirteen years and the SL-RAT acoustic inspection data collected over the past two years.

METHODOLOGY

Acoustic Inspection – SL-RAT Operation

The sewer-line rapid assessment tool (SL-RAT™) exploits the similarities and differences between water and sound transmission through a sewer line segment in order to diagnose the extent of the pipe's blockage. This novel, patented methodology (Howitt 2009) is based on measuring the signal received from an active acoustic transmission through a segment. Figure 2 depicts the general configuration of the SL-RAT device. The acoustic transmitter generates sound waves just below the entrance to the manhole which naturally couple into the connecting sewer line segments, whether the depth of the manhole is 3 feet or greater than 20 feet. The sound wave propagates in the air gap above the wastewater flow from the speaker to the receiving microphone located at the adjacent manhole. Segment lengths exceeding 700 feet have been successfully evaluated. The acoustic receiver measures the acoustic plane wave from the transmitted signal in order to evaluate the condition of an entire segment and provides an onsite assessment in less than three minutes. An important practical aspect of the SL-RAT is that both the speaker and the microphone are placed just within the opening of the manhole and never come in contact with the wastewater flow and the operators have no requirement for confined space entry.

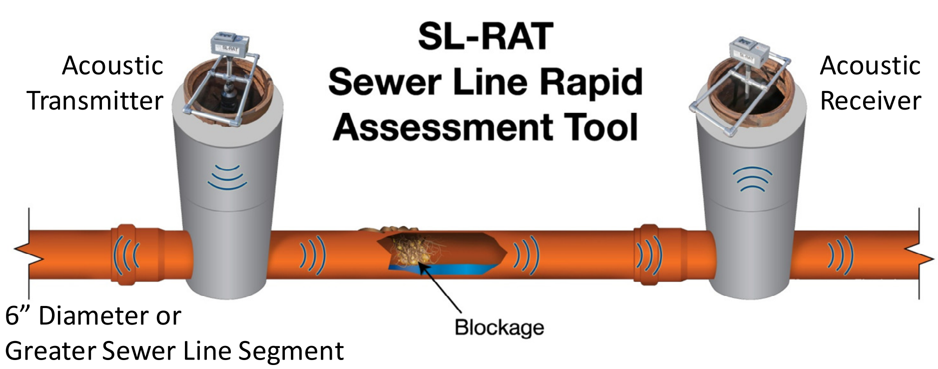


Figure 2 Concept and operation of the SL-RAT Acoustic Inspection System.

A pipe segment is a natural acoustic waveguide (Philip 1968). As illustrated in Figure 2, commonly encountered sanitary sewer defects, such as roots, grease, pipe sags and pipe breakages naturally absorb or reflect acoustic energy. These defects change a segment's acoustic properties and produce a measurable impact on the received signal at the microphone, i.e., the segment's acoustic fingerprint (SAF). Each segment has an individual SAF representative of its current state. The SAF changes over time as the condition of the segment varies. The SL-RAT uses the SAF to determine the SL-RAT Blockage Assessment, i.e., an estimate of the aggregate blockage within the pipe segment between the acoustic transmitter and acoustic receiver. The aggregate blockage assessment is provided to the operator at the end of each test on a scale from 0-10 with zero indicating complete blockage and ten indicating an essentially clean segment. Using the blockage assessment, the operator can determine whether or not maintenance is needed.

Case Studies

CMU Pilot Project integrated the SL-RAT evaluation into an ongoing preventative maintenance program which focuses cleaning and inspection resources into a consolidated area. A detailed presentation of both the approach and the results of the pilot project are presented in Howitt and Fisburne (2010). Key points from this paper are summarized here due to their importance in validating the SL-RAT and to establish its operational performance. The performance results from this study are important for developing and motivating the SL-CBM program based on the SL-RAT.

CMU Pilot Project objectives:

1. Assess the ability of the SL-RAT acoustical tool to
    a. Reveal a state of partial obstruction in a pipe segment,
    b. Define the progression of partial to complete obstruction for a pipe segment.
2. Establish the suitability of the SL-RAT acoustical tool for CMU to realize operating cost savings and prevent system failures
    a. Economically identify pipe segments requiring maintenance (prioritization aid, failure prevention method),
    b. Establish optimal maintenance cycles (sustainable failure prevention).

Approach used in evaluating the CMU Pilot Project objectives:

1. Use the following data collection sequence within the Consolidated Cleaning Area:
    a. Collect pre-cleaning acoustical profile of pipe segments
    b. Collect pre-cleaning video inspection of pipe segments
    c. Collect post-cleaning video inspection of pipe segments
    d. Collect post-cleaning acoustical profile of pipe segments
2. Analyze and assess acoustical profiles and compare with assessment based on video inspections.
3. Evaluate SL-RAT use by CMU field staff to identify reduced capacity within pipe segments without the benefit of having a previous acoustical profile
    a. Define and analyze range of profiles for clean pipes,
    b. SL-RAT classification analysis: False Positive Rate and False Negative Rate
    c. Cost saving analysis.

The pipe segments to be evaluated by the SL-RAT acoustic inspection were based on the pre-cleaning requirements for the basin cleaning project. CMU has found that pre-cleaning needs to be an integral part of a consolidated cleaning project in order to reduce the risk of spills during their systematic cleaning operation. Prior to Basin 17-100 cleaning operations, an Engineering Assessment was made on which pipe segments were at high risk of being obstructed. These pipe segments were then used to define the pipe segments included in the SL-RAT acoustic testing as indicated in Figure 3 by the highlighted pipe segments.

The pre-cleaning classification results in Figure 3 are based on using the SL-RAT Blockage Assessment to evaluate the pre-cleaning classification. The SL-RAT acoustic inspection successfully identified the pipe segments requiring pre-cleaning. The number of pipe segments identified was approximately one-third that identified originally using CMU's standard method of Engineering Assessment using historical data. These results were confirmed using CCTV, as presented in the following discussion.

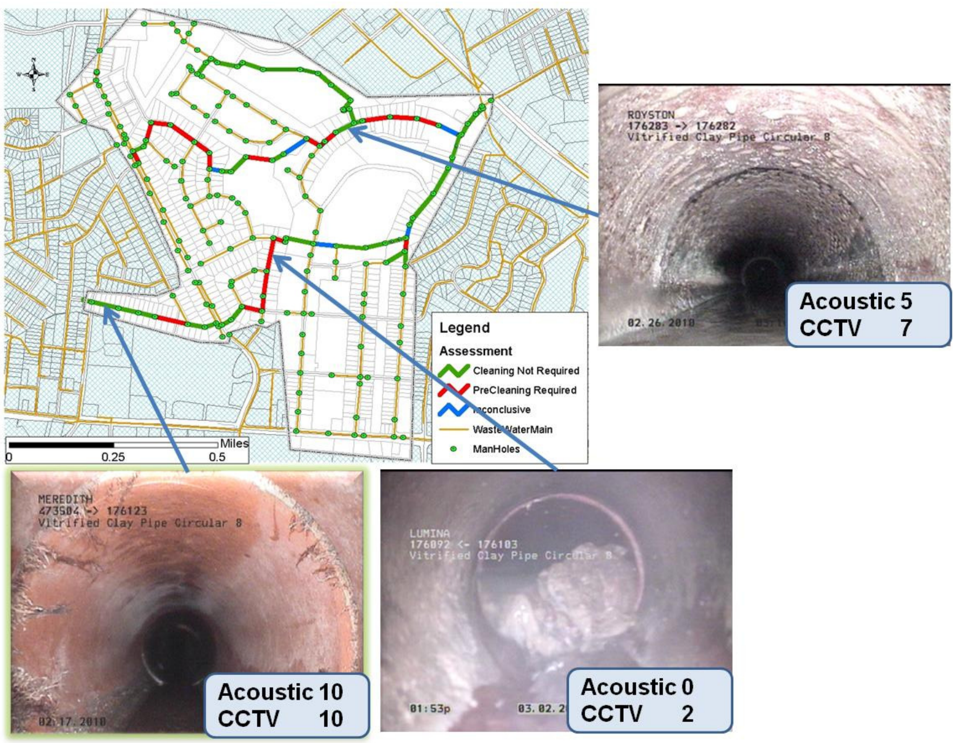


Figure 3 GIS map for Basin 17-100, CMU Pilot Project location. Highlighted pipe segments represent locations evaluated with the SL-RAT acoustic inspection. The three CCTV snapshots illustrate comparison between the SL-RAT Blockage Assessment and the CCTV Blockage Assessment.

An important aspect of the methodology employed in the CMU Pilot Project was collecting CCTV videos both prior-to and after cleaning the pipe segments. This approach allowed the technical feasibility of the SL-RAT to be validated. In order to make a comparative analysis between the CCTV and the SL-RAT, the CCTV videos were independently reviewed to assess the aggregate blockage within each pipe segment, i.e., CCTV Blockage Assessment. A rank order was used in the assessment with 10 indicating a pipe segment was essentially clean and 0 indicating a pipe segment was substantially obstructed. Three examples are given in Figure 3 comparing the CCTV Blockage Assessment with the SL-RAT Blockage Assessment with an accompanying CCTV snapshot to illustrate the condition of the pipe segment.

The scatter plot in Figure 4 provides a comparison based on the two assessments. Each point on the plot represents the CCTV Blockage Assessment versus the SL-RAT Blockage Assessment for one pipe segment. If the two assessment where identical, then all the points would lie along the diagonal line from (0, 0) to (10, 10). As observed in Figure 4, almost all points in the scatter plot lie in the triangle below the diagonal. This implies the SL-RAT Blockage Assessment will tend to be more conservative than the CCTV Blockage Assessment. The scatter plot also indicates a threshold can be established for the SL-RAT Blockage Assessment which allows us to discriminate between essentially clean and essentially dirty pipe segments. This is indicated as the SL-RAT Standard Threshold in Figure 4. Using this threshold, all pipe segments with a SL-RAT Blockage Assessment less than the threshold would require cleaning and all those above would be classified as sufficiently clean and not require additional maintenance. Based on the pipe segments evaluated for the CMU Pilot Project, using the SL-RAT Standard Threshold, a 61% reduction in the cleaning requirement is recommended. A second threshold is indicated on the graph, SL-RAT Critical Threshold. This threshold discriminates between pipe segments in critical need of maintenance and those that are not. Using this threshold indicates 85% of the pipe segments in the CMU Pilot Project are not in need of immediate maintenance, based on the acoustic inspection. On the other hand, 15% should have immediate action taken, whether it is cleaning or a more detailed inspection such as CCTV. The results recommended using the SL-RAT Thresholds are consistent with the CCTV Blockage Assessments. For both of the SL-RAT Thresholds considered, there is no failure in identifying a pipe segment which required further maintenance as one that did not.

To estimate the SL-RAT cost savings, we need to estimate the cost for operating the SL-RAT by a two person field crew. The assumptions used are given in Table 1 where the values in the table reflect typical industry values. The onsite work hours per day has been selected conservatively. The average number of segments inspected per hour using the SL-RAT is based on CMU/InfoSense field experience using the SL-RAT during the course of the CMU Pilot Project. The inspected segments per hour varied from 4 to 10 with 6 being the average. This productivity estimate continues to hold based on CMU’s extensive use of the SL-RAT with several different field crews. Using the values from Table 1, the SL-RAT operational cost per foot is

$$\frac{2\times 68000+24000}{251\times 5.5\times 6\times 220}=\$0.09/\text{ft} \tag{1}$$

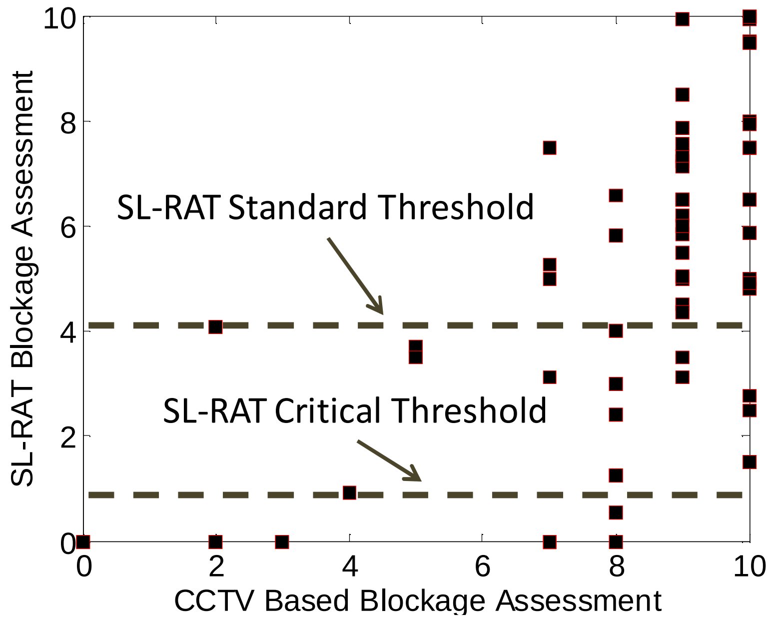


Figure 4 Scatter plot comparing the CCTV Blockage Assessment with the SL-RAT Blockage Assessment for sewer line segments within the CMU Pilot Project. SL-RAT Thresholds used to discriminate between those pipe segments requiring additional maintenance (below the threshold) and those that do not (above the threshold).

Table 1 Assumption Used for Evaluating SL-RAT Cost Based on the CMU Pilot Project

Number of Crew Members	2
Annual Fully Loaded Salary	$68,000
Annual Equipment Costs (Including Truck & SL-RAT)	$24,000
Work Days Per Year	251
Onsite Work Hours Per Day	5.5
SL- RAT Average Number of Segments Inspected Per Hour	6
Average Sewer Line Segment Length in feet	220
Cost Per Foot	$0.09/ft

Next, in order to evaluate the SL-RAT cost-performance, we need to first estimate the cost of the cleaning operation without the SL-RAT. The CMU Current Basin Cleaning Operation is based on cleaning an entire basin followed by CCTV inspection to verify the cleaning operation. For the evaluation we have used one dollar as the average costs per foot ($1.00/ft) for both the CCTV crew inspection and the cleaning crew operation. To generalize the results, we have used typical industry cleaning and CCTV costs and not specific values from the CMU Basin Cleaning

Project. To simplify the evaluation, we have excluded the cost for easement cleaning and clearing. Using these assumptions, the Current Basin Cleaning Operation cost per foot of sewer line pipe is $2.00/ft.

The cost saving analysis for the SL-RAT Based Basin Cleaning Operation needs to balance the cost increase associated with using the SL-RAT with the cost savings obtained by reducing the number of segments to be cleaned. Ideally, we would eliminate all segments requiring minimal maintenance. Using the SL-RAT Standard Threshold reduces the number of pipe segments by 61%. In addition, using this SL-RAT threshold, no pipe segments requiring cleaning are missed. The cost saving is driven by the difference between the total cost estimated for the CMU Current Basin Cleaning Operation and the total cost estimated for the SL-RAT Based Basin Cleaning Operation:

$$\text{CMU Current Basin Cleaning} = \$2.00/\text{ft} \times \text{Number Feet}, \tag{2}$$

$$\text{SL-RAT Based Basin Cleaning} = \left[\$0.09/\text{ft} + (1-0.61)(\$2.00/\text{ft})\right] \times \text{Number Ft}, \tag{3}$$

$$\begin{aligned} \text{Cost Savings} &= \left[\$2.00/\text{ft} - \left[\$0.09/\text{ft} + (0.39)(\$2.00/\text{ft})\right]\right] \times \text{Number Feet} \\ &= \$1.13/\text{ft} \times \text{Number Feet}. \end{aligned} \tag{4}$$

<u>Basin Cleaning Project</u> was conducted to further test and to fully implement the use of the SL-RAT within a basin cleaning project. The goal of the project was to use acoustic inspection to discriminate between pipe segments requiring cleaning and those that do not (Charlotte 2011). A 52,000 ft basin within CMU's collection system was selected. The basin selected was scheduled for consolidated cleaning which would typically require the entire basin to be cleaned and then videoed with CCTV. Instead, acoustic inspection was used to assess the cleaning requirements within the entire basin prior to cleaning. A more conservative SL-RAT Standard Threshold was used for the project, i.e., the threshold was set to 6 rather than 4 as used in the CMU Pilot Project. The results of the acoustic inspection are depicted in Figure 5. With the acoustic inspection results, cleaning was reduced to 22,000 ft (42% of the basin). The 30,000 ft (58%) of sewer which passed the conditional assessment required no maintenance, i.e., cleaning or post cleaning verification. In addition, seven of the eleven segments classified as "Blocked" were found to be full pipe sags and were scheduled for repair. Using the same cost analysis as given in equations (2) –(4), the cost savings for the Basin Cleaning Project was

$$\begin{aligned} \text{Cost Savings} &= \left[\$2.00/\text{ft} - \left[\$0.09/\text{ft} + (0.42)(\$2.00/\text{ft})\right]\right] \times \text{Number Feet} \\ &= \$1.07/\text{ft} \times 52{,}000 = \$55{,}640. \end{aligned} \tag{5}$$

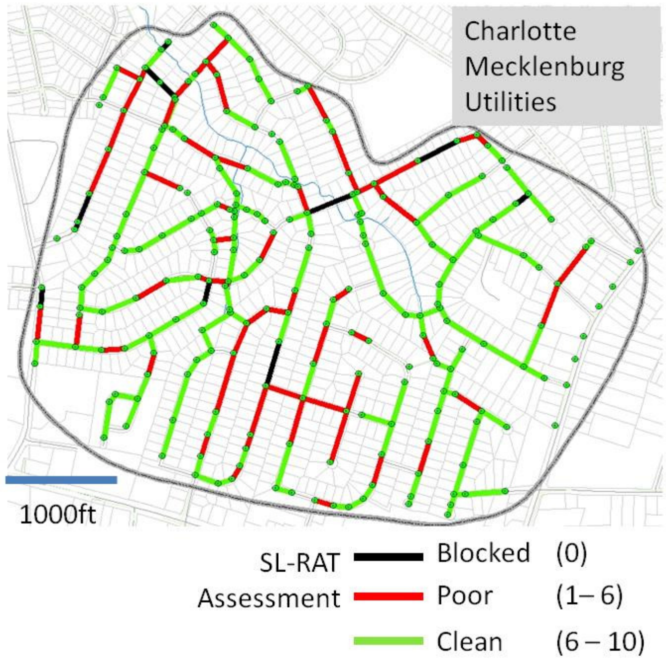


Figure 5 SL-RAT acoustic inspection assessment for Basin Cleaning Project. Prior to cleaning 58% of the basin classified as "Clean" and no further maintenance action was required.

CONDITION BASED MAINTENANCE PROGRAM

Overview

Maintenance policies for wastewater collection systems' cleaning operations are currently a combination of fixed interval maintenance, i.e., Time-Based Maintenance (TBM) and reactive maintenance, i.e., Corrective Maintenance (CM). Figure 6(a) illustrates the optimal region of application for each strategy. The horizontal axes represents the remaining time to failure with values decreasing towards the right. The vertical axis represents the relative risk and the cost associated with a pipe segment overflow. To illustrate, vandalism can lead to overflows, e.g., dumping leaves in a manhole. Since vandalism is an unlikely event and the time to failure is short, a CM program is the only option. A TBM program is appropriate in areas where periodic cleaning interval is required and can be reliably estimated, e.g., areas with high grease restaurants. In these areas there is a high risk and the time interval to failure can be predicted.

A preponderance of grease and root blockages occur over a sufficiently long time interval, suggesting a CBM program is optimal. From Wiseman et. al.,

> "Condition based monitoring is defined as: an identifiable physical condition which indicates that a functional failure is either about to occur or in the process of occurring. In this process, the items are inspected and left in service on the condition that they meet specified performance standards. The frequency of these

inspections is determined by the potential failure (P-F) interval, which is the interval between the emergence of the potential failure and its decay in to a functional failure."

Developing an overall maintenance policy that balances the maintenance strategies is the goal of Reliability Centered Maintenance (RCM) (Moubray 1997). RCM allocates cleaning resources based on optimizing the cost and risk associated with overflows.

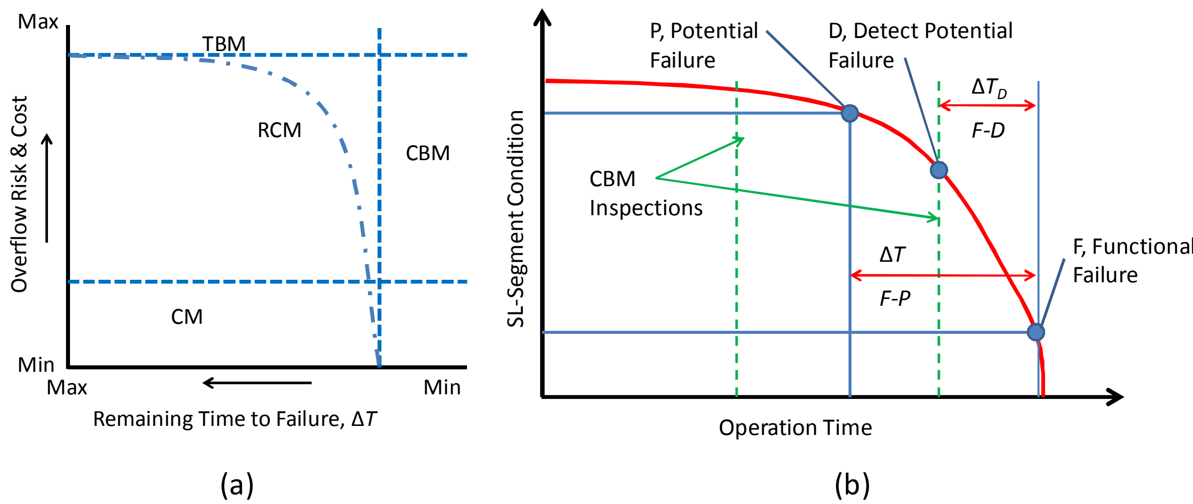


Figure 6 (a) Regions of optimal application for four maintenance strategies (Lehtonen 2006); (b) Relationship between inspection and P-F in a CBM based maintenance strategy (Moubray 1997 and Wiseman et. al.).

Historically, using condition based inspection to determine where and when to deploy collection system cleaning resources has not been economically feasible. The available inspection technologies are either cost prohibitive or provide inadequate information. The SL-RAT acoustic inspection equipment provides a clear condition assessment directly correlated with the cleaning requirements. Acoustic inspection requires significantly fewer resources compared to normal maintenance, i.e., SL-RAT acoustic inspection has been shown to be less than 1/10th the cost of cleaning or just \$0.09/ft. This provides the opportunity to rethink using condition based maintenance as a viable tool for deploying cleaning resources. This approach can improve maintenance quality, reduce unnecessary maintenance operations and, at the same time, reduce costs.

The previous discussion motivates the value proposition for implementing the Sewer Line Condition Based Maintenance (SL-CBM) program based on the SL-RAT inspection. Figure 6(b) illustrates the concept and the challenges with implementation. The graph in the figure is a standard P-F curve (Moubray 1997 and Wiseman et. al.) depicting a graceful degradation in a pipe segment with the condition assessment graph representative of a grease or root mode of failure. Point P represents the initial time performance degradation can be detected and Point D represents the time performance degradation is detected based on the SL-RAT CBM inspection schedule. Point F represents the operation time at which the sewer line pipe segment functionally fails, e.g., the blockage is sufficient to cause an overflow. Each pipe segment has a unique P-F curve governed by underlying factors influencing its failure rate. The goal of the SL-CBM is to estimate the CBM inspection and maintenance times to ensure maintenance is scheduled and conducted prior to the pipe segments failure at a significant cost savings over current maintenance programs.

The SL-RAT is an essential tool in developing an effective SL-CBM cleaning program. To explore the significance of an SL-CBM cleaning program, we extrapolate the results from the CMU Pilot Project. The graph in Figure 7 provides a hypothetical comparison of the cost effectiveness between three cleaning programs. The purpose of the comparison is to illustrate the flexibility and trade-offs available in designing a cleaning program based on acoustic inspection. We draw upon the results of the linear regression in Figure 1 to set a performance goal for the collection system cleaning program. From the linear regression, to achieve an operations performance goal of 2 overflows/100 miles/ year, requires 76% of the collection system to be maintained annually. The corresponding one standard deviation below the mean requires 45% of the system to be maintained. This result is translated to Figure 8 where the blue region highlights the range of possible solutions for the collection system cleaning cost/100 miles of pipe to be within the corresponding 45% to 76% system maintenance requirements.

In Figure 7 at Point-1, for the baseline cleaning policy, 20% of the pipes are cleaned annually at $1/ft. For this cost analysis we only consider the cost of cleaning and do not include any cost for post cleaning inspection with CCTV. The other two polices are based on using the acoustic inspection tool prior to cleaning. For these two policies, 20% of the pipes have been inspected and, based on their SL-RAT Blockage Assessment, only 7.8% are estimated to require cleaning resulting in over a 50% cost savings. Only segments which are diagnosed as essentially clean are removed from the cleaning operations resulting in no impact on collection system performance.

Next we look at keeping the budget fixed at the 20% annual baseline cleaning cost and look at two different cleaning and inspection policies using the SL-RAT. For SL-CBM I, we continue using the policy that only essentially clean line segments are removed from the cleaning operations based on their acoustic blockage assessment. This allows us to acoustic inspect 41.6% of the collection system and based on the SL-RAT Blockage Assessment only 16.2% require cleaning, Point-2. SL-CBM II takes a different approach by switching modes to focus on only cleaning the pipe segments which are in immediate need, i.e., only clean if diagnosed with a significantly low SL-RAT Blockage Assessment. The policy transfers more resources towards inspection rather than cleaning, allowing 63.4% of the collection system to be acoustic inspected, with an estimated 14.1% cleaned and with an estimated 9.5% diagnosed as having a significant blockage assessment by the SL-RAT acoustic inspection tool, Point-3. This suggests that by using acoustic inspection, over 60% of the collection system can be maintained annually at a comparable cost as a 20% annual baseline cleaning program. This achieves the goal of maintaining the collection system between 45% and 76% without increasing the annual cost. The SL-RAT acoustic condition assessment is used to cost effectively target cleaning resources to locations with a higher likelihood to cause overflows.

The previous discussion provides a general assessment of SL-CBM program using the SL-RAT acoustic inspection. Variations in implementation are examined under the assumption that overflows are equally likely within the collection system. We next turn to evaluating the SL-

CBM cost versus performance impact taking into account the historical spatial overflow patterns within CMU's collection system. In addition, characteristics of the SL-RAT performance are incorporated based on CMU's operational acoustic inspections over the past two years.

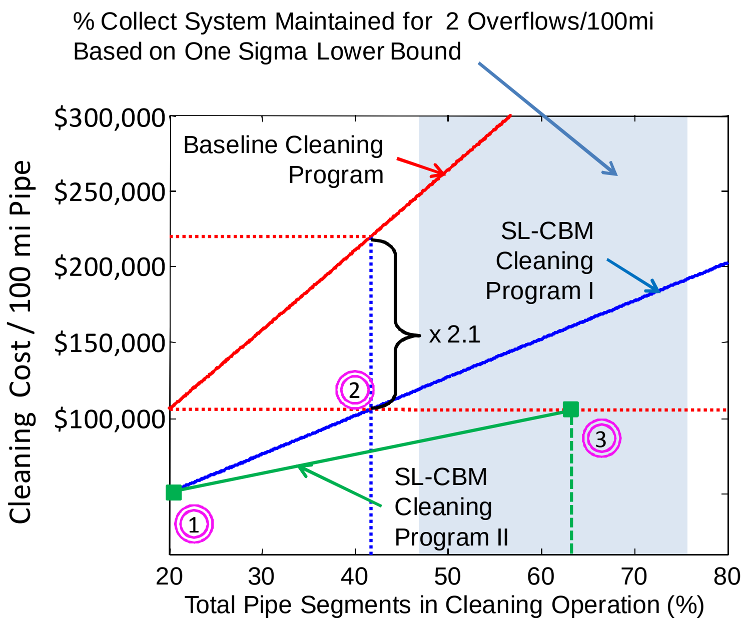


Figure 7 Collection System cleaning policy comparison between Baseline Cleaning Program with two different Condition Based Maintenance programs (SL-CBM Program I & SL-CBM Program II) which use SL-RAT acoustic inspection to prioritize cleaning operations.

CMU SSO Evaluation

Understanding the spatial and temporal distribution of overflows within the collection system plays an important role in developing and managing a maintenance program. The following evaluation is based on CMU data collected for FY 2000 through FY 2012 (FY 2012 data is through May 24, 2012 and the CMU fiscal year ends June 30th). Figure 8(a) shows a spatial distribution of the 4,386 overflows within the collection system over the past thirteen year period. The distribution is based on evaluating the number of overflows occurring within one-square-mile based on a one-square-mile grid overlaid on Mecklenburg County. The County boundaries are indicated by the dashed black lines in the figure. The overflows occur within 390 square miles of the 526 square miles of the CMU collection system. Overflow occurrence is well correlated with collection system pipe density and population density.

Variation in overflow density is strongly evident in Figure 8(a). The overflow distribution is further investigated by evaluating the histogram of the overflow occurrence within each one-square-mile. The histogram is given in Figure 8(b). The overflow distribution has been grouped into four regions as indicated by four colors. Region 0 includes the 136 one-square-mile locations with no reported overflows in the past thirteen years. Region I through Region III are defined based on the overflow ranges specified in the figure's legend. Above each corresponding Region in the histogram, the following two items are given: the total number of overflows within the region and the number of square miles encompassed by the region.

The regions identified in Figure 8(b) help identify areas within the collection system requiring different levels of priority for allocating maintenance resources based on the historical overflow data. To illustrate, the 136 square miles with zero reported overflows, Region 0, requires minimal change in resources allocated to it or perhaps even a reduction in resources is warranted. Whereas, Region III includes 80 one-square-mile locations with each location averaging over two overflows per year; Region III locations would be good targets for reducing the annual overflow rate. This segmentation will be further exploited in evaluating the overflow characteristic within CMU and in developing the CMU SL-CBM program based on the SL-RAT.

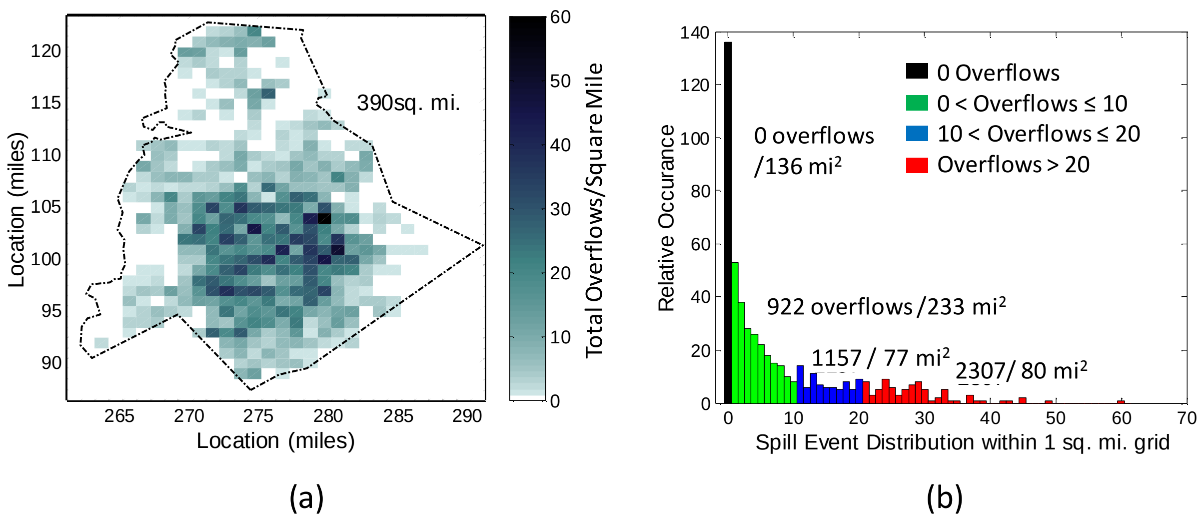


Figure 8 CMU SSO Evaluation for FY 00 through FY12 (a) Spatial representation of the overflows that occurred within one-mile-square grid over the thirteen year period; (b) Histogram of the number of overflows that occurred within a one-mile-square over the thirteen year period with the bar color distinguishing between three disjoint regions.

Figure 8 provides an aggregate historical perspective on the distribution of overflow events within the collection systems, but does not provide an indication of when they occurred. To obtain a different perspective, the temporal occurrence of the overflows is examined. In Figure 9, moving averages are provided based on the CMU's recorded date for each overflow occurrence within FY 2000 to FY 2012. The moving averages are normalized to provide the overflow rate per 100 miles of linear feet of pipe occurring in a year, i.e., overflows/100mi./year. Both three month and twelve month moving averages are depicted in Figure 9. Seasonal variations in the overflow rate are evident in the three month moving average. In addition to the moving average, the past four year trend in the overflow rate is evaluated by linear regression over the 12 month moving average. Both the graph of the linear regression and the ±50% confidence for the linear regression is depicted in the figure. The slope of the linear regression provides a measure of the annual rate of change in the overflows/100mi. The slope is -0.6, indicating a reduction in the overflows/100mi of 0.6 for each of the past four years. The terminal date for the linear regression is November 2011. Evaluating the linear regression for this date, the overflow rate is 7.3 overflows/100mi. Using the same approach, temporal characteristics of the overflows in Regions I, II and III are evaluated. Figure 10 provides the corresponding graphs and Table 2 summarizes data associated with both the temporal and the spatial overflow evaluation. These results will be used in developing and evaluating the CMU SL-CBM program based on the SL-RAT.

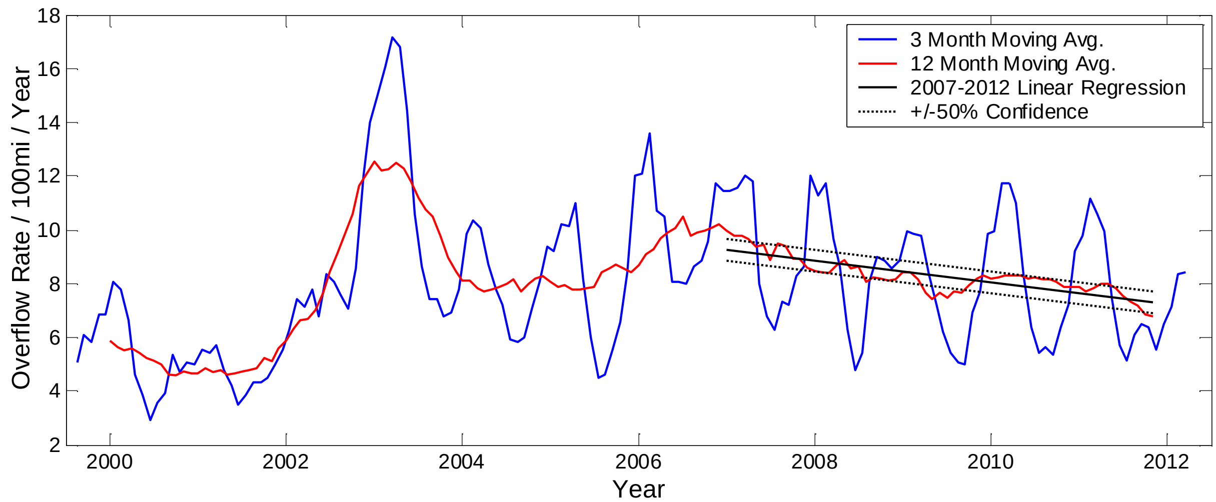


Figure 9 Both short time and long time moving averages of the Overflows / 100miles normalized to a one year time interval based on the CMU SSO data for FY 00 to FY 12.

Table 2 CMU Overflow Temporal and Spatial Data Summary Based on FY 00 to FY 12.

	Entire Collection System	Region 0	Region I	Region II	Region III
Total number of overflows	4386	0	922	1157	2307
Number of square miles	526	136	233	77	80
Number of linear miles of pipe line	4261	437	1869	874	1081
Overflow/100mi rate of change (linear regression slope, Figure 9 and 10)	-0.6	0	0.4	-1.4	-1.7
Overflow/100mi at November 2011 from linear regression Figure 9 and 10	7.3	0	5.1	8.2	13.4

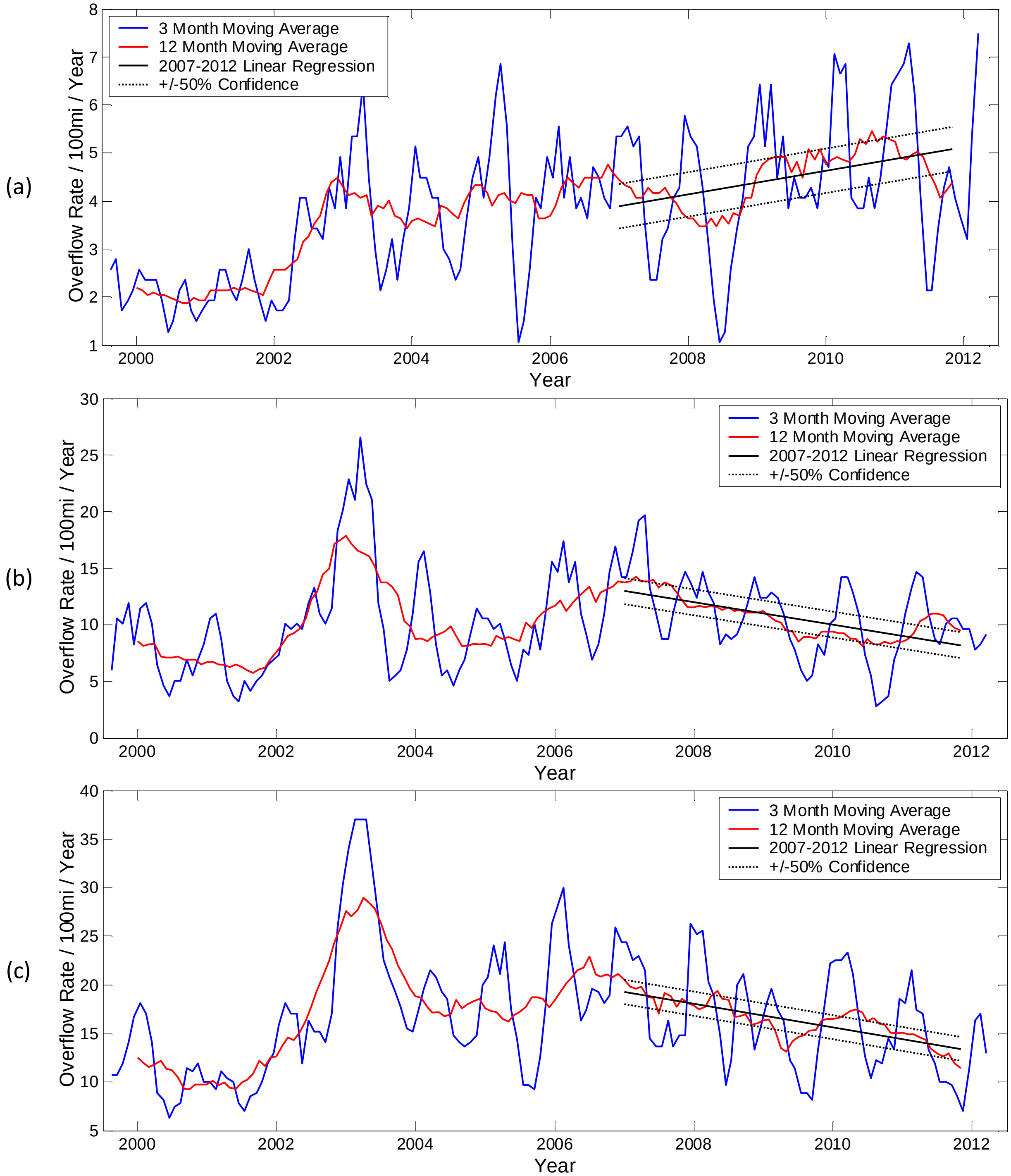


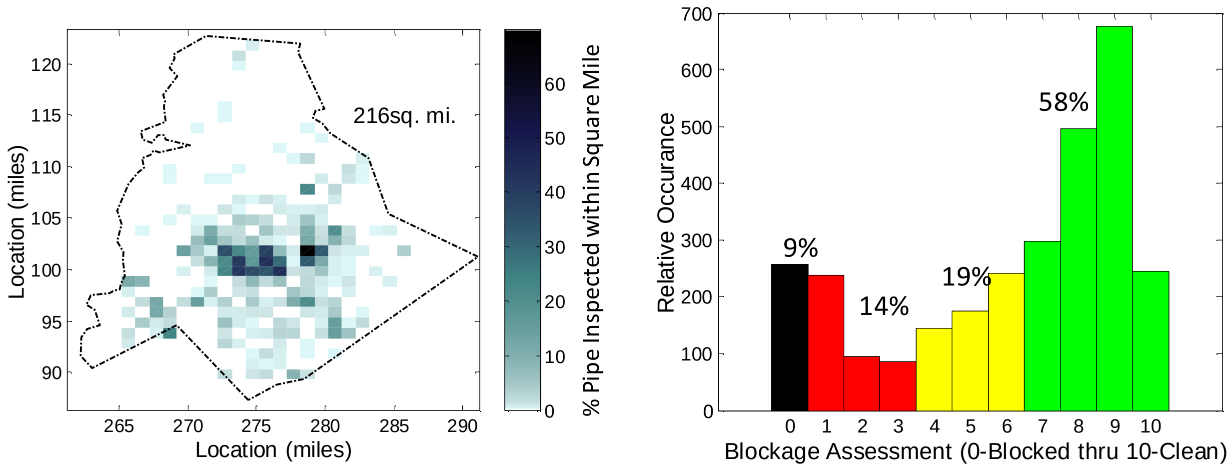
Figure 10 Both short time and long time moving averages of the Overflows / 100miles normalized to a one year time interval based on the CMU SSO data for FY 00 to FY 12 (a) Region I – 0<Overflows/SqMi≤10; (b) Region II 10<Overflows/SqMi≤20; (c) Region III Overflows/SqMi > 20.

CMU Acoustic Inspection Evaluation

Over the past two years CMU has conducted well over three thousand SL-RAT acoustic inspections of pipe segments. This has provided a condition assessment for over 850 thousand feet of the collection system. In the past year, the focus of the inspections has changed from evaluating the SL-RAT technology, to incorporating the technology as the enabler for a newly evolving collection system cleaning CBM program based on acoustic inspections.

Figure 11(a) provides a spatial representation for the SL-RAT acoustic inspection locations conducted by CMU. The spatial representation is based on a one-square-mile grid system; the same system used in evaluating the overflows in Figure 8(a). For each one-square-mile location, the percentage of pipe inspected by the SL-RAT over the past two years is indicated. The inspections included in the evaluation are restricted to those inspections conducted prior-to cleaning operations. This included almost three thousand measurements.

By comparing Figure 11(a) with Figure 8(a), an important observation is that the SL-RAT acoustic inspections were conducted predominately within either moderate or high overflow locations, i.e., Region II and III. Using this observation, then the SL-RAT Blockage Assessment provides an estimate for the cleaning requirements within the CMU collection system biased towards locations which are historically more prone to overflows. The corresponding histogram of the SL-RAT Blockage Assessments is given in Figure 11(b). Based on the classification employed by the SL-RAT: 58% of the pipe segments are considered Good, 19% Fair, 14% Poor, and 9% Blocked. The pipe segment condition assessment is an important component in developing and evaluating the SL-CBM program. An additional refinement would be to evaluate the SL-RAT Blockage Assessment for each region (Region I, II and III) individually. To date, the SL-RAT measurement data set does not support estimating the blockage assessment distribution in each Region. Therefore, the distribution in Figure 11(b) is used to represent the three regions.



(a) (b)

Figure 11 CMU Acoustic Inspection – (a) Spatial representation of the percentage of pipes inspected within each square mile grid; (b) Histogram of the blockage assessment.

CMU SL-CBM Program Evaluation

The hypothetical SL-CBM evaluation presented in the Overview is extended by incorporating the CMU SSO evaluation presented in the previous section and the CMU acoustic inspection program implemented over the past year. To date, insufficient data and insufficient time has elapsed to allow direct evaluation of the SL-CBM program being established at CMU; therefore, a performance model is derived based on the empirical data collected to date.

The approach is to evaluate the Cost associated with the SL-CBM program based on establishing a new collection system cleaning program to achieve a desired number of overflows/ 100mi of linear pipe, i.e., the performance goal

$$P_T = \frac{O_T}{N_T} \tag{6}$$

where O_T is the total number of overflows within the collection system based on the utilities maintenance program and N_T is the number of 100mi lengths of pipe within the collection system. The evaluation model is derived to evaluate the total cost of the maintenance program

$$C_T = \sum_i C_i \tag{7}$$

where C_i is the cleaning operation cost for the i^{th} Region. The value of C_i is evaluated for two cases: Cleaning Only program with no Acoustic Inspection and SL-CBM program based on Acoustic Inspection, i.e.,

$$C_i = C_C\, A_i N_i \quad \text{[Cleaning Only no Acoustic Inspection]} \tag{8}$$

$$C_i = \left[C_C\, A_i + C_I I_i\right] N_i \quad \text{[SL-CBM with Acoustic Inspection]} \tag{9}$$

where C_C is the cost to clean 100mi length of pipe and C_I is the cost to acoustic inspect 100mi length of pipe with the SL-RAT. A_i is the fraction of the i^{th} Region cleaned and I_i is the fraction of the i^{th} Region inspected with the SL-RAT. For the SL-CBM program, A_i is determined based on the SL-RAT Threshold used to discriminate between pipe segments requiring cleaning and those that do not. The relationship between the SL-RAT Threshold and the fraction of pipe segment cleaned, D, is derived based on the CMU acoustic inspections and the relative occurrence of blockage assessments as depicted in the histogram in Figure 11(b). The SL-RAT Thresholds evaluated are the same as those used in the case studies presented above and the values D for the SL-RAT Thresholds are given in Table 3. Then using $A_i = D\, I_i$, the SL-CBM cost for the i^{th} Region's is

$$C_i = \left[C_C\, D + C_I\right] I_i\, N_i \quad \text{[SL-CBM with Acoustic Inspection]} \tag{10}$$

Next, the total number of overflows is given by

$$O_T = \sum_i O_i\, N_i \tag{11}$$

where O_i is the number of overflows/100mi of linear pipe in the i^{th} Region and N_i is the number of 100mi lengths of pipe in the i^{th} Region.

From the graphs in Figure 10, the overflows/100mi for the i^{th} Region can be estimated for the CMU maintenance program prior to the effect of the acoustic inspection. These values are estimated based on the linear regression and are given in Table 2 and are used in evaluating O_i. To evaluate O_i, the new maintenance program performance needs to be evaluated in terms of the former maintenance program. Using this approach, the i^{th} Region's overflow/100mi is modeled by

$$O_i = R_C A_i - R_C F_i + R_i \quad \text{[Cleaning Only no Acoustic Inspection]} \qquad (12)$$

$$O_i = R_C I_i - R_C F_i + R_i \quad \text{[SL-CBM with Acoustic Inspection]} \qquad (13)$$

where for the SL-CBM program it is implicit that the fraction of the i^{th} Region cleaned is $A_i = D I_i$. R_C is the rate of change in the number of overflows/100mi based on the change in the fraction of the area maintained (cleaned or inspected). F_i is the fraction of the i^{th} Region cleaned under the former maintenance program and R_i is the overflow/100mi in the i^{th} Region based on the former maintenance program.

Table 3 Parameter Values Used in Evaluating the SL-CBM Program Cost-Performance

Parameter	**Value**
Fraction of pipe segments cleaned, *D*, for SL-RAT Threshold 1	0.17
Fraction of pipes segments cleaned, *D*, for SL-RAT Threshold 3	0.23
Fraction of pipes segments cleaned, *D*, for SL-RAT Threshold 5	0.34
Ratio SL-RAT acoustic inspect cost to cleaning cost, C_I/C_C	0.09
Rate of change in the number of overflows/100mi to the change in the fraction of the collection system area maintained, R_C	-7.8

R_C is an important parameter in evaluating the effectiveness of a maintenance program. It specifies the rate in achieving the performance goal based on either cleaning more pipe segments or by improving the selection process for targeting cleaning resources to the pipe segments requiring cleaning. R_C is estimated using the slope from the linear regression from the scatter plot data depicted in Figure 1. For the results presented in the paper, the value is considered a constant. This provides a first order approximation. R_C is likely to be region dependent and dependent on the maintenance program followed, i.e., for the SL-CBM program, R_C will be impacted by the SL-RAT Threshold selected. As the SL-RAT Threshold is increased, the number of pipe segments scheduled for cleaning increases. In addition, the cleaning targets pipe segments which are increasingly cleaner. Therefore, the value of R_C will initially rapidly improve with a diminishing improvement as the SL-RAT Threshold increases. This relationship has not been established and therefore is not used in evaluating the results in the paper.

The desired model for relating the total cost in terms of the overflows/100mi of linear pipe is obtained by combining equations (6) through (13)

$$C_T = \frac{N_T\,K}{R_C} P_T + K \sum_i F_i\,N_i - \frac{K}{R_C} \sum_i R_i\,N_i \tag{14}$$

where
$$K = C_c \quad \text{[Cleaning Only no Acoustic Inspection]} \tag{15}$$

$$K = C_c\,D + C_I \quad \text{[SL-CBM with Acoustic Inspection]} \tag{16}$$

Looking at the three terms in equation (14) provides insight into the model. The first term, $(N_T\,K/R_C)P_T$, provides the head room savings based on the performance goal being greater than zero overflows/ 100mi. The second term, $K\sum_i F_i\,N_i$, is the cost of meeting the Former maintenance performance using the new maintenance program and the third term, $(K/R_C)\sum_i R_i\,N_i$, is the cost of mitigating the reported overflows based on the new maintenance program.

By relating equations (15) and (16), the mechanism for achieving substantial cost savings using the SL-CBM over the Clean-Only program can be readily evaluated. For the same performance goal, the SL-CBM will be less expensive than the Clean-Only program given

$$\begin{aligned} C_c &> C_c\,D + C_I \\ \frac{C_I}{C_c} &< 1 - D \end{aligned} \tag{17}$$

As discussed in previous sections, the cost of acoustic inspection is, conservatively, less than a tenth the cost of cleaning. In addition, the fraction of pipe segments not requiring servicing ($1-D$) are at least 50% and often significantly greater. The inequality in equation (17) is well met, leading to substantial cost savings for the same performance goal.

The total maintenance program cost, C_T, is evaluated using equations (14) through (16) based on varying the performance goal, P_T. Graphs of the evaluation are depicted in Figure 12. The cost in Figure 12 has been normalized by the estimated cost for cleaning 20% of CMU's collection system ($0.2N_T C_C$). This normalization removes the uncertainty associated with cleaning cost, C_C. The parameter values used in evaluating the equations are summarized in Tables 2 and 3. Three SL-CBM programs are compared based on using different SL-RAT Thresholds. These results are compared to the program based on Cleaning-Only.

From Figure 12, a SL-CBM program using an SL-RAT Threshold of 3, results in a performance of four overflows/ 100mi without increasing cost. To achieve the same performance with the Clean-Only program requires over 3 times the cost.

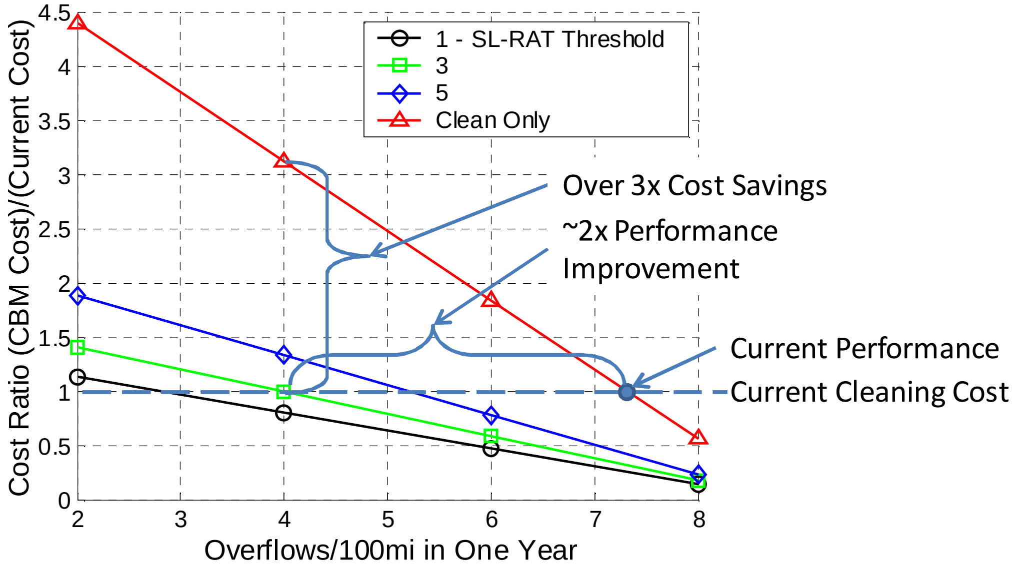


Figure 12 Cost versus performance evaluation for the SL-CBM. Cost is evaluated based on the ratio between the cost of the SL-CBM program with the cost of the current cleaning program, i.e., Cleaning 20% of the Collection System/Year. Performance is based on the number of overflows per 100 miles in a year.

SUMMARY & CONCLUSIONS

In summary, we have explained the basic operational principles of a new pipe inspection technology and shown through several examples from Charlotte-Mecklenburg Utilities, (CMU), multiple ways that active acoustic inspection can significantly improve the maintenance cost and performance of gravity-fed wastewater collections systems. This patented technology is embodied in a device called the Sewer Line Rapid Assessment Tool or SL-RAT which has inspected over 850 thousand feet of pipe during the past two years of field use.

The underlying novel technology itself was described to make the principle of operation clear. The SL-RAT is composed of two components – a transmitter and receiver which are each placed in adjacent connected manholes. The transmitter generates sound waves that naturally couple into the pipe segment. The sound waves propagate in the air gap within the pipe segment. The receiver measures the acoustic plane wave received from the transmitter and, through a proprietary algorithm, evaluates the condition of the pipe in the form of a blockage assessment. This blockage assessment is an aggregate measure of the blockage level within the pipe and is scored on a relative scale of 0 to 10. The blockage assessment scale is empirically correlated with CCTV where zero means fully blocked and ten means the pipe is fully clear.

Additionally, multiple operational benefits of the SL-RAT relative to existing alternatives were covered. The SL-RAT does not require confined space entry and does not contact the wastewater flow making it safer to operate. It also does not require the support of cleaning equipment, provides the blockage assessment in 3 minutes or less, has been practically operated in a typical wastewater collection field environment under a variety of conditions, and can be easily operated by a field crew of two operators.

The results of multiple pilots and field studies conducted by CMU in conjunction with Infosense were reviewed which show the efficacy, the economics, and the operational advantages of the SL-RAT device. The efficacy of acoustic inspection technology was highlighted in a study conducted by CMU and InfoSense to correlate CCTV video with the aggregate blockage measurement provided by the SL-RAT. Acoustic inspections were shown to successfully detect blockages within a pipe segment and to provide acceptable resolution for delineating when pipe cleaning activity should take place and when it should not. This same field study estimated the cost of operating active acoustic inspection equipment and found that the SL-RAT's relatively low cost of operation combined with detecting where the high cost of cleaning pipes can be avoided can generate savings in the range of $1.07 to $1.13 per foot inspected.

Finally, we looked at extending the use of acoustic inspection technology to enable the establishment of a Condition Based Maintenance (CBM) program for gravity-fed collection system pipe maintenance. An example was illustrated using data from CMU to extrapolate that for a system targeting 2 overflows/100 miles/year, implementing an SL-RAT-enabled CBM program could reduce cleaning costs by 50% or more. The improvement compounds as more resources are shifted to the relatively cheaper task of acoustic inspection and away from the relatively expensive and partially wasteful task of scheduled pipe cleaning. The financial benefit comes through better focusing cleaning crews on blocked pipes and away from cleaning pipes that do not need cleaning. These results were extended further to develop a performance model which illustrates mathematically that using SL-RAT data as part of a CBM program can provide significant benefits to wastewater system operators by producing BOTH a significant positive impact on overflow performance as well as system maintenance costs.

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