PROBABILITY BASED SCHEDULING TO OPTIMIZE SEWER MAINTENANCE

BY

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THESIS

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ABSTRACT

With municipal administrations and EPA (Environment Protection Agency) concentrating more on the issue of SSOs (Sanitary Sewer Overflows), sewer failures have been studied much in recent years. This thesis focuses on the blockages of sewer lines, which cause nearly half of the SSOs. A simulation model is developed to analysis efficiency of different inspection programs. A combined factor, which affects the interval time between blockages, is described by two-parameter distribution. Each pipe in the sewer system has characteristic parameters and distribution that is also utilized to simulate the operation of sewer system in the model. Fitting the parameters from historical database, estimated parameters are used to predict blockages. Two methods (Birnbaum-Saunders Distribution estimation and Median estimation) to estimate the parameters are compared from the accuracy and operation time aspects. Meanwhile, failure probability in certain period is calculated from the distribution to support the maintenance schedule, which leads to a probability-based inspection strategy. To ensure the effect of this strategy, a line-by-line inspection strategy in which inspected pipes are selected randomly is also studied. The results show that the strategy with highest inspection efficiency is the probability-based one with parameters estimated from BSD estimation method. Moreover, economic analysis of the strategies is studied to optimize the capital investment of maintenance and the civil penalties regulated by EPA.

ACKNOWLEDGEMENT

I would like to thank my advisor, professor Arthur Schmidt who help me come up with the roughly idea of this research and guide me step by step to accomplish the work. Without his support, the thesis is not possible to be completed.

I would like to thank all the hydro group, especially the ones in my research group. I learned much from our both academic and relaxed group meetings. I thank their comments on my work which help me better improve my research and produce inspirations when I was stuck.

I would like to thank all my friends who for their patience to listening to my troubles in life and work, and encourage me to overcome all the obstacles. I would like to thank my family: my parents and all my relatives, who care me and support me from another side of the earth.

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CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

Sanitary sewer overflows (SSOs) has become a popular term in the consent decrees made between EPA (Environmental Protection Agency) and US states. Where SSOs happen and when the consent decree is effective, civil penalties are imposed on the metropolitan city. In 2011, Oakland paid the Regional Water Board $280,000 for its penalty of SSOs (California Consent Decree, 2014). The Consent Decree also forces the city Alameda to inspect all the sewer lines within 10 years to eliminate SSOs (California Consent Decree,2014). Similar terms can also be found in other consent decrees such as Maryland Consent Decree and Pennsylvania Consent Decree, which describe the response and monitoring of SSOs problems. Wirahadikusumah et al. (2001) mentioned that sewers comprise the most consuming part of infrastructure maintenance investment - around $18 per person or $3,435/km of sewer. SSOs have become a severe problem for regulators from both environmental and public aspects (Sumer, Gonzalez & Lansey, 2007).

Different from most European countries, in the USA, separate sewer systems substitute combined sewer systems gradually (Sier & Lansey, 2005). Therefore, SSOs become a totally distinct problem from the overflow caused by sudden rainfall in combined sewer systems. Sewer system is the public infrastructure that is expected to be operating with no interruption (Berardi, 2009). In the USA, however, with the increase of population and development of food establishment, larger amounts of grease and debris are discharged into collection system. These accumulate and buildup to eventually cause blockages of sewer lines that ultimately result in SSOs (Dominic et al., 2013; LANDUARS, 2013). Though the reasons of SSOs vary widely, including condition of pump station, sudden increasing discharge capacity etc., blockages contribute around 50% of the sewer failures (Aziz et al., 2011).

Universal management strategies for SSOs problems is costly inefficient. The strategy to repair whenever failure occurs is becoming less economically feasible as the systems age (Rokstad & Ugarelli, 2015). However, cities still invest much on the problem. New York, which has serious sewer backup problems, planned to spend $2.4 billion to develop sewer monitoring program in next decade (The State of The Sewers, 2013). More organizations are now focusing on the visual inspection systems, such as closed conduit television(CCTV), to inspect sewers which is really expensive. The San Antonio Water System(SAWS) in Texas estimates that they will pay nearly $1.1 billion on the CCTV programs in next 10 years (LANDUARS,2013).

To address the SSOs caused by blockages, this thesis tries to utilize statistical method to develop a simulation model that is able to predict the blockage probability of certain pipes based on historical data. The strategy also indicates the priority of pipes that should be inspected and cleaned to optimize the maintenance investment.

The motivation of this thesis is to model the failure time series of sewer systems and use the prediction to support maintenance schedule, which helps the municipalities minimize inspection investment and sewer failures that will lead to penalties. Failure of pipe lines in the model mainly focus on the blockages that result from combined factors of human activities and natural deterioration of pipes. The issue here is random and hard to study mechanisms that need to be modeled with distribution fitting process. The simulation model in this thesis provides future failure prediction based on the historical failure data. The model is also utilized to create maintenance time table. Moreover, this maintenance strategy is compared with line by line inspection strategy to show the inspection efficiency. In the last parts of the paper, the optimization of minimizing costs and penalties is also mentioned.

1.2 Thesis Objective and Main Work

Main objective of project is to develop the approach and tools to optimize sewer maintenance schedule based on probability model. The objectives are to: 1) improve understanding of fitting process to estimate distribution parameters from history data, 2) develop stochastic simulation tools for large urban sewer system to predict blockages, 3) develop tool to simulate maintenance-scheduling practices, 4) simulate the maintenance costs and overflows and thereby determine regulatory (e.g. penalties) and operational strategies to optimize system.

The research studied a probability-based inspection strategy and developed a simulation model, which is utilized to test the inspection strategy. The general model is set to simulate the sewer system without any inspection behavior. This means that the pipes are only cleaned when they are blocked and SSOs happen. To discover the proper maintenance strategy, characteristics of sewer lines and statistical distributions are studied. Combining the inspection strategies with the model, the inspection efficiency is observed and investment and penalty of the strategies are also examined. The summary of the main works are as follows:

(1) Select suitable distribution to fit for the historical dataset and define parameters for sewers with no recorded failures and when maintenance precludes failures.

(2) Develop modeling framework to simulate urban sewer operation system with and without inspection strategies.

(3) Compare different inspection strategies with inspection efficiency and utilize the strategy to support maintenance schedule.

(4) Analyze the economic costs of operating the sewer system with different strategies to optimize capital investment and regulated penalties.

1.3 Outline of Thesis

The chapters of thesis are arranged as follows:

Chapter 2 gives a literature review on previous research of urban sewer failure issues. A variety of methods to model and predict sewer failures.

Chapter 3 describes how this study developed the model framework to simulate the operation of urban sanitary sewer system. Two inspection strategies utilized to support the maintenance schedule are introduced and compared.

Chapter 4 examines the tradeoffs between the number of crews committed to sewer inspection and maintenance, the penalties for blockage-caused SSOs, and the number of failures.

Chapter 5 is the statistical analysis part of this thesis. In this part, distribution selected to support the strategy is presented. Results of inspection efficiency and economic analysis are also shown in this part.

Chapter 6 provides the conclusions, limitations and potential future work of this thesis.

CHAPTER 2: LITERATURE REVIEW

The failure interval time of SSOs could be modeled with certain distributions. However, to select an appreciate distribution is still a focus of researches. Previous research has examined a variety of methods to model sewer failur. Based on the idea of Kingman (1993) that Poisson distribution family could be used to simulate continuous random process, Jin and Mukherjee (2010) selected exponential distribution and Weibull distribution to simulate the sewerage failure process of a small town in Michigan. Both of the distribution fit sewer failure data successfully. They also suggested that probability of failures could be calculated to support inspection programs, which is one of main goals of our research. Berardi et al. (2009) planned sewer inspections with multi-objective genetic algorithms and combined inspection cost with the model. Recently, Del Giudice et al. (2016) used multivariate probability distribution to fit the sewer failure data from Naples. Using multinormal distribution function, Del Giudice et al. (2016) developed his own model and calibrated it. More simulation model work has been done, Saagi et al. (2015) developed a benchmark simulation model to evaluate the control strategies for urban sewer networks. From studying these previous modeling work, sewer failures could be modeled and simulated based on distributions and the probability could be utilized in the prediction part.

Other works focused on prediction part after the failure model was completed. Abraham et al. (1998) studied sewer deterioration mechanisms and developed probability-based Markovian prediction models. In their study, optimization techniques were also utilized to maximizing benefit/cost ratios. Another method was provided by Jin and Mukherjee (2010) that probability of failures could be calculated from distribution function to support inspection programs. Also, Salman and Salem (2012) determined risk of failure from combining probability value and the sequences of failure value. Works of Jin and Mukherjee(2010), Salman and Salem(2012) and Abraham et al. (1998) indicate that probability theory could be an effective method to perform the prediction of sewer failures. Other kind of prediction work are also done by researchers. Baah et al. (2014) supposed a risk-based approach to manage sewer system using consequence of failure model. Moreover, Harvey and Mcbean (2014) utilize random forest to predict operating condition of sanitary sewers.

Though some works have been done on modeling and prediction of sewer failures, the study of economic inspection and cleaning strategy is relatively lacking, which is one of the goals of this thesis. Most municipalities in U.S. now are using Closed Conduit Television (CCTV) to detect the condition of sewers, which is costly and time consuming. For example, to improve visual inspection management on city sewers, San Antonio consent decree require the utility spend nearly $500 million beyond the roughly

$600 million planned capital costs over the next decade, for a total cost of $1192 million (LANDUARS, 2013).

The idea of CCTV is developed in about last two decades. Through using a camera in the pipes, users can observe the operating conditions inside the pipes and acquire a perception of whether the pipes are going to fail. Coding for the program is developed into different types. CEN (2010) studied European standard EN13508-2 coding system for CCTV camera and analyzing system. Also, Gemora (2003) present North American PACP Coding system. However, to develop an inspection program like this, specific equipment is necessary, with a camera and a piece of codes inside to analyze the visual materials, which is costly. To reduce the large investment caused by CCTV equipment, Fuchs-Hanusch et al. (2015) made suggestions that CCTV should be only used on the pipe segments that fail frequently. They also mentioned another visual inspection program, Manhole Zoom Cameras (MZC's) which is less costly but of less accuracy. Fuchs-Hanusch et al. (2015) suggested that MZCs could be used on low frequently failed segments. In CCTV inspection program, cameras go from one end to another end of a line, while in MZC's inspection program, cameras are only put in the manhole and zoomed in to see the pipelines from the ends. More recently, Plihal et al. (2016) proposed that when combined with acoustic devices, MZC models could become a "cost-effective alternative" to CCTV.

This thesis is trying to develop a “costless but effective” method based on the modeling and prediction of sanitary sewer failures. The model will be based on a certain distribution and the prediction will be based on probability calculation. Inspection strategies developed from the prediction indicates the priority of maintenance and optimized capital cost. The inspection strategies from the proposed model could be used to schedule any type of inspection or maintenance, from CCTV to MZC.

CHAPTER 3: SIMULATION MODEL AND INSPECTION STRATEGY

3.1 Model Parameters

The historical data of interval time between two failures of a certain pipe should follow certain patterns which we believe could be described by distributions. Two parameters are set to describe the distribution that fits the data, *MTTF* and *gamma*. *MTTF* (Mean Time To Failure) indicates the mean value between two failures of a given pipe. *Gamma* is used to show the shape of the distribution.

Each pipe is assumed to have two real parameters that can indicate its characteristics of blockage time series: *MTTF* and *gamma*. In the model, *MTTF* and *gamma* are used to simulate the operation of sewer line. However, for real world sewer system, real *MTTF* and *gamma* are impossible to get. Thus, estimated *MTTF* and *gamma*, which are the results of calculation from historical failure database are utilized to do the prediction. The error between estimate parameters and real parameters depends on the completeness and preciseness of the dataset.

In this thesis, the comparison of estimated *MTTF* and real *MTTF* was tested to ensure the accuracy of the inspection program. Two methods are implemented to estimate *MTTF* and the results are compared. The first one is to set shape parameter gamma as 1.0 and fit the dataset with distribution to get *MTTF*. The second one is to fit dataset with distribution to get both *MTTF* and *gamma*, which is more accurate than the former method but consumes more time as well. The two methods are compared in accuracy and time in order to suggest which one is better to be utilized in the model based on the requirement of the users.

The incompleteness or impreciseness of database will influence the efficiency of the inspections scheduled based on the data. Thus, it is important to find a proper method to deal with datasets with incomplete historical record describing data. Compared with incomplete data, the imprecise database is more preferable (Ahmadi et al., 2013). If it is assumed that the database contains complete records for recent years, lines lacking failure records are interpreted as having no failures in the period of record. In this case, parameters will be defined based on the record time and their construction time.

The model is applied for a long period of 5 years. The result is a history of failure times for each pipe in the synthetic system. A period of historic records is selected (e.g., 10 years) and then the most recent data for this period are examined to estimate the *MMTF* and *gamma* values for each pipe. If a pipe has had no failures in the period of data, *MTTF* and *gamma* for that pipe are set to the duration of the period of historic data and 1.0, respectively.

3.2 Simulation Model Framework

The model simulates the operation process of sewers in given time period. The inputs of the model include the previous failure historical data, total running time period and inspection work load in each time period. Then, the model will fit the historical data of a certain line with a specific distribution and provide distribution parameters. With these parameters, a particular inspection strategy is selected to inspect and clean the lines. Condition of sewers in this time period (which pipes fail and which pipes are cleaned) is recorded and then next time period begins.

The general simulation model simulates the condition when sewer system is operating without any maintenance. This means that the sewer lines are never maintained before blockages happens. Whenever there is a failure reported, crews are send to clean the failures. The process of the general simulation model is shown in Figure 3-1.

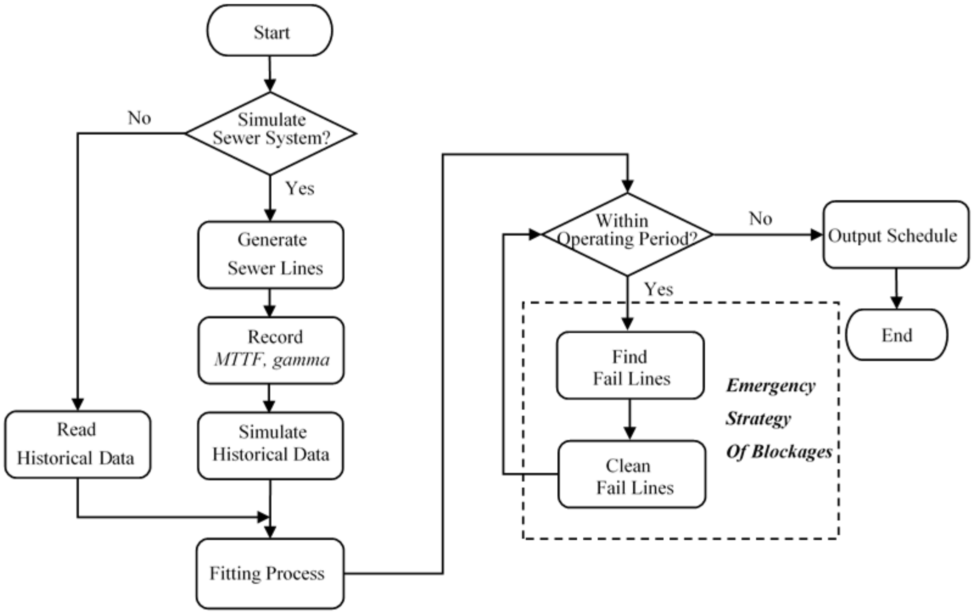

Figure 3-1 Flow Chart for General Simulation Model

The model is tested for a synthetic sewer system for which the value of *MTTF* and *gamma* are known for every pipe. The distribution of values of *MTTF* and *gamma* are based on investigations of existing networks. While the proposed approach should ideally be tested using a real-world system, most municipalities do not have sufficiently long records describing the history of failures and inspection for every pipe in the system to determine the true statistical distribution for failures. By simulating for a synthetic network, we can produce a long period of failure data and then sample from these data to examine the impact of applying the proposed approach to systems with limited period of records available. The first step of this process is to simulate a sewer system based on the investigation of real world sewer system. This simulated sewer system is like a real world one but the different thing is that real value of *MTTF* and *gamma* could be stored and utilized in the later calculation.

However, in the real world system, the real value of *MTTF* and *gamma* cannot be determined. Instead, values of *MTTF* and *gamma* will are estimated based on historical failure records. If the actual *MTTF* and *gamma* values for the pipes (the values used to simulate the performance of the synthetic system) were used in operation simulation and prediction calculations in inspection strategy, the results of inspect efficiency may be too high beyond real efficiency. Therefore, to make the model more realistic, the parameters used to simulate performance of the synthetic system should be real value and parameters used in inspection strategy should be estimated ones.

The emergency action to SSOs in this model is a fail-clean regulation which follows the normal rules of municipal administrations. In this simulation model, the sewer systems will be checked in each time period to find which pipes are blocked and they are cleaned in the same time period.

The condition of each pipe is transformed into values and stored as two numbers, *LastClean* and *NextFail*. *LastClean* is the interval time between operating time period and the last day when the pipe fails or is cleaned, which can also be interpreted as the time difference from the inspection day and last clean day of the pipe. *Nextfail* is a prediction of future failure of the pipe, which indicates how many days later will the pipe fail. As time progresses, *LastClean* will increase and *Nextfail*, on the contrary, will decrease until the pipe fails again. When a pipe fails, the *Nextfail* will becomes zero and at the same time, the model will simulate a new *LastClean* value for the cleaned pipe based on the distribution and parameters.

3.3 Inspection Strategy

The probability-based inspection strategy is to utilize the distribution function to predict the probability of failure for a specific pipe at a certain time. Probability of blockages in a specific time period are calculated for every pipe, and the pipes with highest failure probabilities are set to be inspected and cleaned in the maintenance schedule. The number of pipes inspected in a period is a key parameter and is based on the number of crews available and the number of pipes they can clean or inspect in a period.

To test the inspection efficiency of the probability-based inspection strategy, one-by-one inspection strategy is also studied to simulate the operation. In this strategy, pipes are inspected and cleaned one by one from the database and workers keep working on different pipes on each day. This strategy is a more random one where the number of pipes inspected in a period is the same as the probability-based strategy, but with random selection of pipes.

Inspection strategies are combined with simulation model to show their working efficiency. The simulation model (with the 'real' values for MTTF and gamma) is used to determine which pipes will fail in a period. If a pipe that was not scheduled for inspection fails, the model requires that that pipe be cleaned at a higher priority than any inspections. As a result, some of the pipes that were scheduled for inspection will not be inspected because of the work capability of workers.

When a pipe fails, the failure is included in the record for that pipe and the estimated best fit values for *MTTF* and *gamma* are recalculated for that pipe. When a pipe is cleaned or inspected, the *LastClean* parameter is reset and a new time to the next failure is recalculated using the simulation model.

The process continues to the next time step by calculating a new set of failure probabilities, using the estimated *MTTF* and *gamma* values and the updated *LastClean* values.

Flow chart of model with inspection strategies is shown in Figure 3-2. The inspection strategy consists of two process: Failure Prediction process and Inspect-Clean process. Failure Prediction process will output pipes that may fail and in the Inspect-Clean process, these pipes are cleaned. Difference of probability-based strategy and line-by-line strategy is in the Failure Prediction process. For probability-based strategy, the pipes are chosen from calculation of probability while for line-by-line strategy, pipes are chosen one by one randomly.

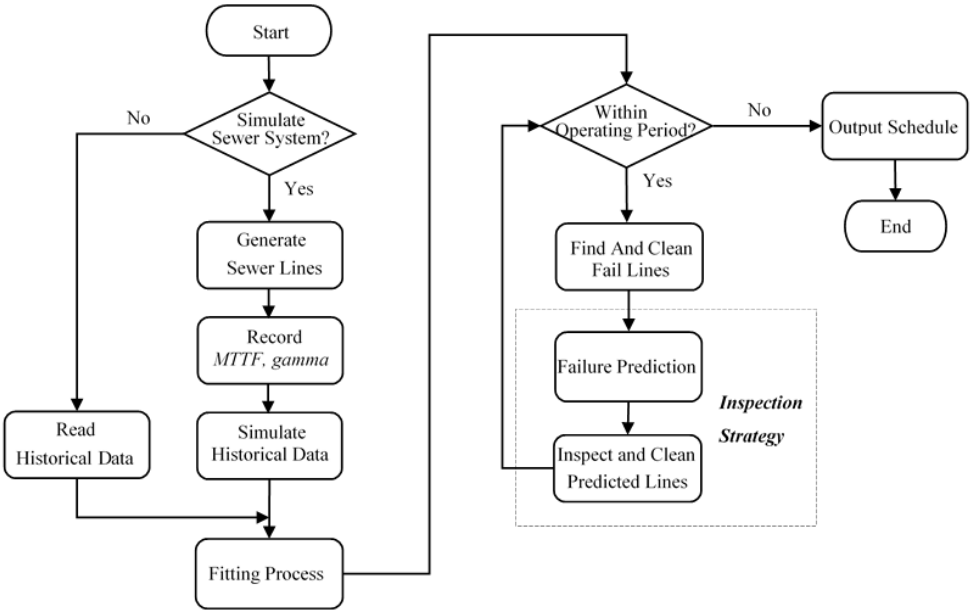

Figure 3-2 Flow Chart for Model with Inspection Strategy

CHAPTER 4: ECONOMIC ANALYSIS

Total capital investment of sewer maintenance at blockage aspect consists of inspection cost, cleaning cost and failure penalties.

$$TC = IC + CC + P \qquad \textbf{(Eqn.4-1)}$$

Where TC is the total cost, IC means inspection cost, CC means cleaning cost and P is penalty.

The inspection cost and cleaning cost can be acquired from experience data and are related to crew cost as well as equipment cost.

Based on this objective function, TC needs to be minimized given a regulated penalty. Variable here is the number of pipes that need to be inspected each day. The work load of inspection provides information about how many crews to employ and how much equipment to purchase, which is utilized in cost calculation. Different strategies also result in various cost. Based on the efficiency of strategies, the ratio of penalties to total cost also differs.

One of the goals of this research is to help provide guidance that regulatory agencies can use to set appropriate penalties that will result in failures occurring no more frequently than some acceptable level, while allowing civil administrations the flexibility to manage how they attain the goal. Given a penalty, our model tries to suggest the optimized inspection strategy and maintenance schedule that could minimize capital cost and at the same time reduce sewer failures. When given acceptable failure numbers and inspect capability, the model compares capital cost with various penalties, and output penalty advice.

Inspect capability in the analysis is expressed in two ways. One is to determine how many lines to inspect in one day and another is to determine how many crews are employed to work for the sanitary sewer maintenance. In the model, crews are set to clean already blocked lines first. If they still have working capability after the blocked clean work, the priority lines indicated by the strategy will be inspected.

CHAPTER 5: STATISTICAL ANALYSIS AND RESULT DISCUSSION

5.1 Distribution Selection

To study the behavior of sewer failures, we try to use distribution to describe the pipe blockages. Several distributions were studied and tested, such as exponential distribution and Poisson distribution. We discovered that Birnbaum-Saunders distribution fits best for the failure interval time series. Birnbaum-Saunders distribution (also called Fatigue Life distribution) is often used to predict the failure of continuously working structures. Figure5-1 shows the real probability density curve from historical data and figure5-2 shows our simulation curve. From the two figures, we conclude that the model works well in the fitting process.

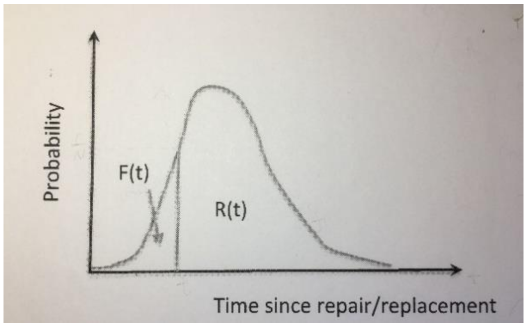

Figure5-1 PDF of Historical Data

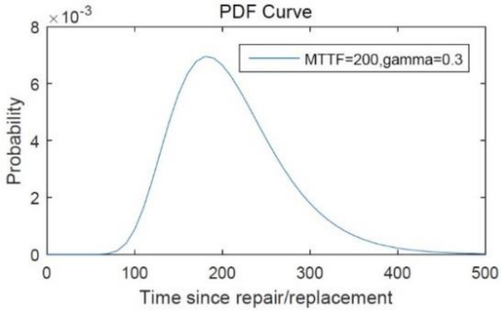

Figure5-2 PDF of Fitting Distribution

The general function of Birnbaum-Saunders distribution is shown below:

$$P(X \le \omega) = \Phi\left(\frac{\omega - n\mu}{\sigma\sqrt{n}}\right) \qquad \textbf{(Eqn.5-1)}$$

In Eqn.5-1, X is the total failure time which follows normal distribution. The mean value of the normal distribution is $n\mu$ and variance is $n\sigma^2$. The Eqn.5-1 represents the probability when total failure times X is less than a critical failure time ω.

After applying the distribution fitting process into the model framework, a specific two-parameter Birnbaum-Saunders distribution is selected for each line with parameters *MTTF* and *gamma*.

Shape parameter *gamma* indicates the stretch direction of the PDF curve and scale parameter *MTTF* (Mean Time To Failure) indicates the mean value. The PDF (Eqn.5−2) and CDF (Eqn.5-3) are as follows:

$$f(t) = \frac{1}{\sqrt{2\pi}} \exp\left\{ -\frac{\left(\sqrt{\frac{t}{MTTF}} - \sqrt{\frac{MTTF}{t}}\right)^2}{2gamma^2} \right\} \left(\frac{\sqrt{\frac{t}{MTTF}} + \sqrt{\frac{MTTF}{t}}}{2 \times gamma \times t} \right) \qquad \textbf{(Eqn.5-2)}$$

$$P(t \le T) = F(t) = \Phi\left(\frac{1}{gamma} \left(\sqrt{\frac{t}{MTTF}} - \sqrt{\frac{MTTF}{t}} \right) \right) \qquad \textbf{(Eqn.5-3)}$$

Where t is TTF (Time To Failure) which is the interval time value between two blockages. $f(t)$ is the fail probability of the pipe at time t after it is cleaned or blocked.

$F(t \leq T)$ indicates the fail probability of the pipe before time T after last clean.

5.2 Estimation of Parameters

Two methods are utilized to estimate *MTTF*: 1)Fit historical data with two-parameter Birnbaum-Saunders distribution and get value of *MTTF* and *gamma* (BSD method), 2) Set value of *gamma* as 1.0 and fit the historical dataset with Birnbaum-Saunders distribution for only the value of *MTTF* (Median Method), which is the same with the median value of historical data.

From statistical aspect to analysis the two method, it is obviously that the first one should be more accurate because two parameters are evaluated. The second method only evaluates one parameter with another one being assumed to a constant value. However, from technology aspect, the first method should be more time consuming than the second one especially when the sewer system is very large. The completeness of dataset is also studied by comparing the estimation results from 5 years data, 10 years data, 15 years data and 20 years data.

5.2.1 Accuracy Of Two Methods To Estimate MTTF

The two methods are experimented to fit both 10 years and 20 years historical dataset generated by simulated sewer system. Because the simulated sewer system is developed by the model, the true values of *MTTF* and *gamma* are also stored. The size of the simulated sewer system is 1000 pipes with *MTTF* values ranging from 90 days to 3650 days and *gamma* values ranging from 0.05 to 1.50. Figures below shows the results.

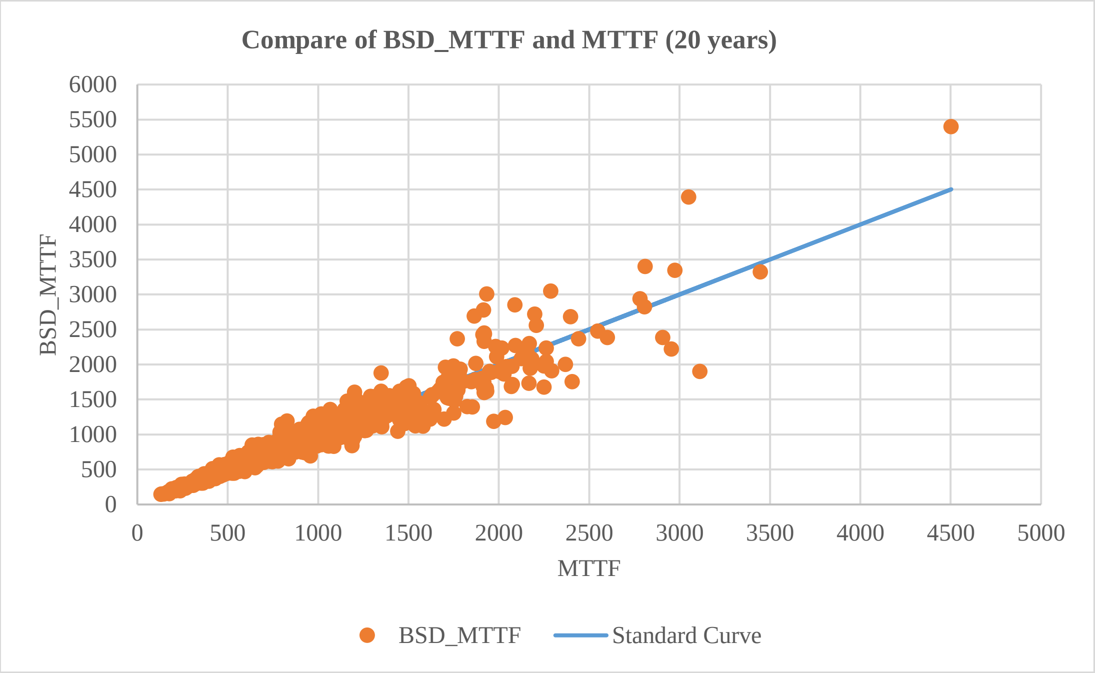

Figure 5-3 Comparison of *BSD_MTTF* and *MTTF* for 20 Years Dataset

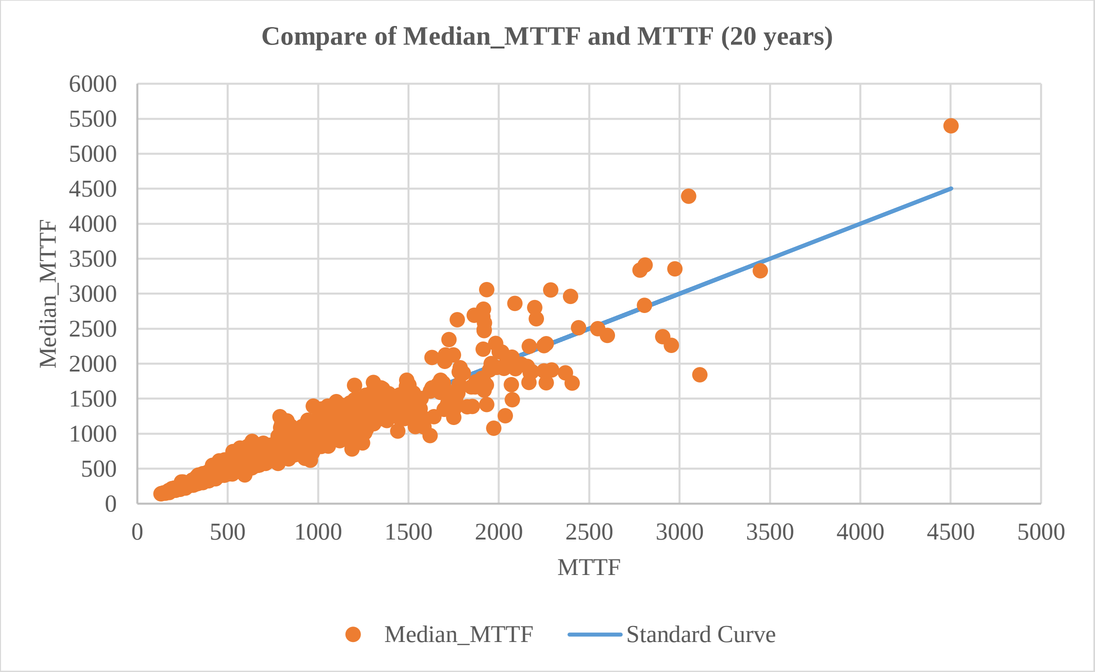

Figure 5-4 Comparison of *Median_MTTF* and *MTTF Fitting* for 20 Years Dataset

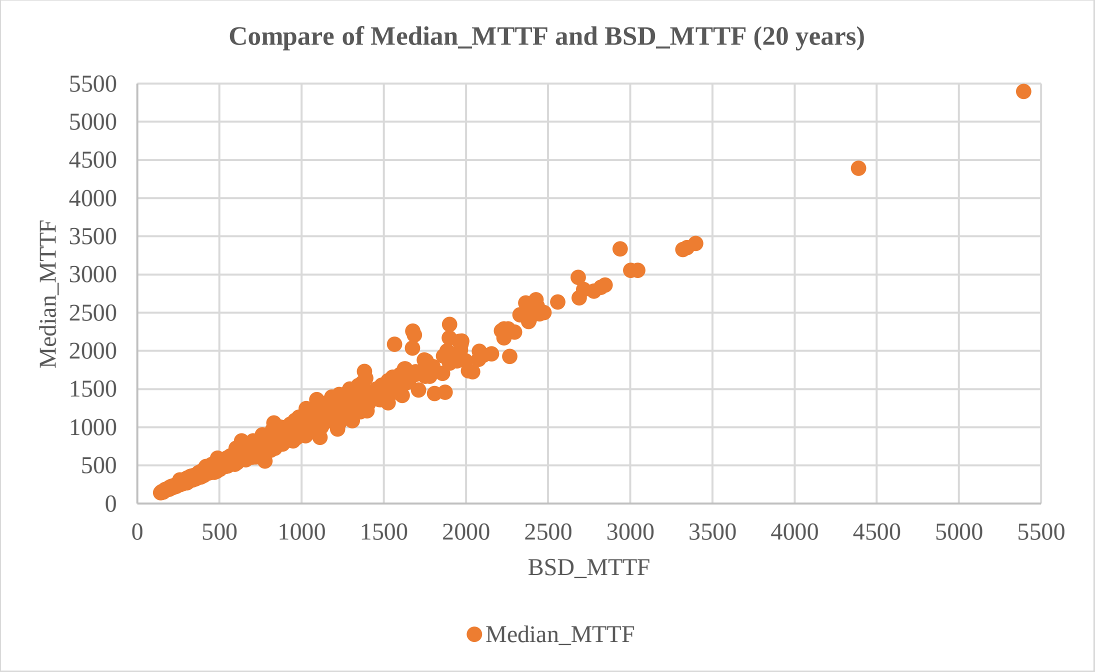

Figure 5-5 Comparison of *Median_MTTF* and *BSD_MTTF* for 20 Years Dataset

The three figures (Figure 5-3, Figure 5-4, Figure 5-5) above show the accuracy of estimated *MTTF* value. In the figures, *BSD_MTTF* is the value estimated from the BSD estimation method and *Median_MTTF* is the value estimated from the Median estimation method. In Figure 5-3 and Figure 5-4, blue line shows the line of perfect fit where estimated value of *MTTF* equals real *MTTF*. Points in both Figure 5-3 and Figure 5-4 are close to the standard curve, which indicates that the estimation is relatively close to the real value.

Comparing Figure 5-3 and 5-4, most of the points are at the same position which means that the two methods provide similar estimation. However, when studied into details, some of the points are still different and the under this circumstances, *BSD_MTTF* is closer to the real value than *Median_MTTF*. For example, for the pipe whose real *MTTF* is 2782 days, the value of *Median_MTTF* is 3334 days while the value of *BSD_MTTF* is 2939 days. This could also be seen in Figure 5-5 which shows the difference of *Median_MTTF* value and *BSD_MTTF* value. R^2 is also calculated to express the accuracy of estimated value. R^2 for *BSD_MTTF* equals 0.9215, larger than R^2 for *Median_MTTF* which is 0.9030.

Both Figure 5-3 and Figure 5-4 show that when *MTTF* is lower, points are more aggregate and closed to standard curve. However, when *MTTF* becomes higher, the estimate values are more inaccurate. This makes sense for that pipes with lower *MTTF* may block more frequently and have more historical data and pipes with higher *MTTF* may only fail once or twice in the recording time period which is really hard to evaluate the parameters. This does not influence much in the maintenance strategy because it is the pipe that fails much in a short time period will bring much inconvenience for the public and brings much penalties and costs for the management administrations. Though the prediction of the pipes with higher *MTTF* may be of lower precision, they will not influence the inspection strategy much, for they may only fail once in five or ten years. Consequently, to have a more precise prediction on the frequently failing pipes is more important.

In addition to *MTTF* analysis, *gamma* value is also important. The effect of *gamma* is shown in Figure 5-6. Real *gamma* values may vary from 0.05 to 1.5 which could be estimated from the first method. The results are similar with the estimation of *MTTF* shown in Figure 5.3 for the Birnbaum-Saunders Estimation Method. However, in the second method, the assumption is that *gamma* value of all pipes are 1.0. This value will affect the shape of the PDF curve. It could even change a right-skewed distribution to a left-skewed one.

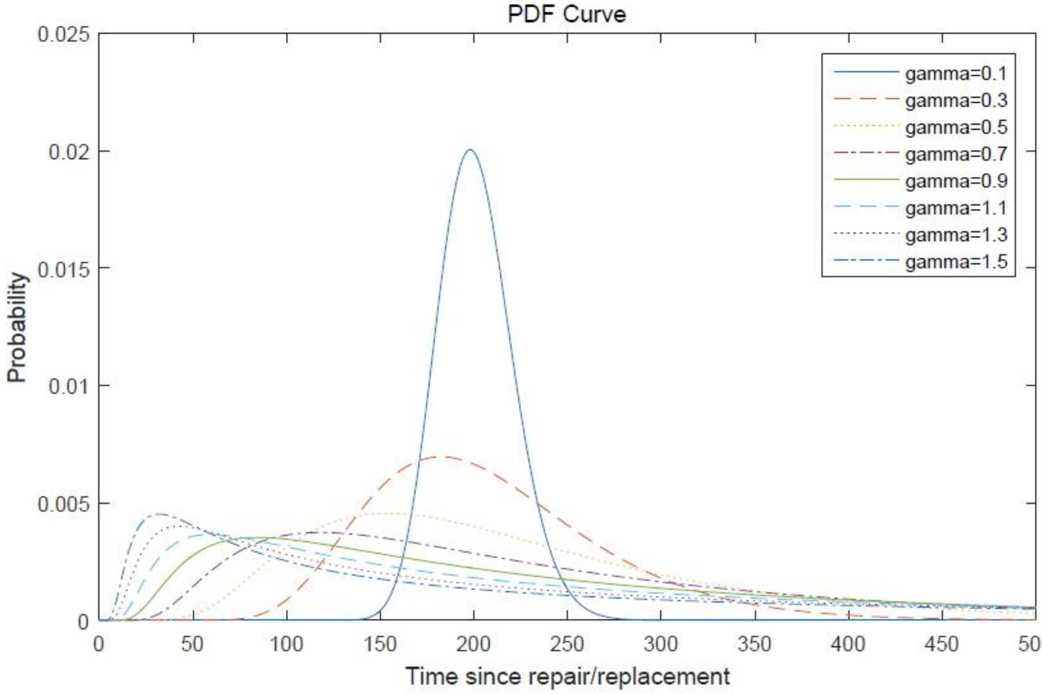

Figure 5-6 Figure Showing How Gamma Effect the Shape of PDF Curve

All the curves in Figure 5-6 have the same *MTTF* (equals 200) and different *gamma* changing from 0.1 to 1.5. The figure shows that with increasing *gamma*, the PDF curve is changing to a more right-skewed one. From investigation, most pipes follow a distribution curve which is a little bit right-scaled and *gamma* should be around 0.3 to 0.7. In the second method, *gamma* is assumed as 1.0 which makes the curve more right-skewed and this may reduce the inspection efficiency of the maintenance strategies greatly.

5.2.2 Operating Time Of Two Methods To Estimate MTTF

Operating time of two estimation methods are also compared based on 10 years historical data of various size of sewer system: 1000 pipes, 3000 pipes, 5000 pipes, 8000 pipes as well as 10000 pipes. The results are shown in the Table 5.1.

Table 5-1 Operating Time of BSD and Median Estimation Methods

Sewer Size/pipes	Operating Time (s)	
	BSD_Estimation	Median_Estimation
1000	24.657	0.089
3000	73.718	0.218
5000	121.085	0.305
8000	200.84	0.524
10000	239.001	0.652

From the table below, the operating time of Median estimation method is much less than the BSD estimation method. This makes sense from technological aspect for the reason that the calculation of Birnbaum-Saunders Distribution parameters is much more complicated than the calculation of median value. The results are also shown in Figure 5-7 to indicate how operating time changes with the size of sewer system.

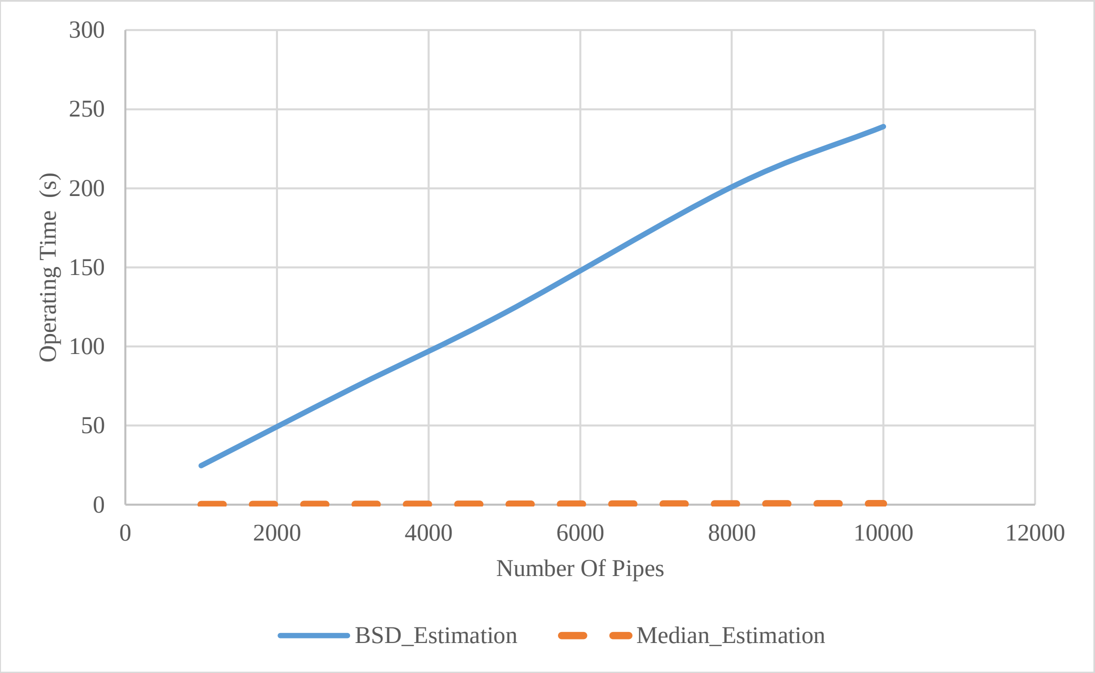

Figure 5-7 Comparison of Operating Time for BSD and Median Estimation Method

In Figure 5-7, the two lines are nearly linear which indicates that the operating time is in proportion to the number of pipes in the sewer system. This is because that the estimation process for each pipe is progressed separately and in sequence. For example, if the sewer system has 1000 pipes, the estimation process will loop for 1000 times to evaluate the parameters of each pipe in the system.

From above analysis, the two methods to estimate MTTF both have their advantages and disadvantages in accuracy and time consumption. The first one is more accurate but consumes more time while the second one is opposite. However, operating time could be decreased using some technology. Hu (2015) mentioned that this kind of separate loop process could speed up by changing it into parallel section. If the 1000 pipe estimation process is divided into two parallel lines – 500 pipes in each line, the total ideal operating time would be reduced into half. Consequently, to ensure the inspection efficiency, the first method is suggested to use in the model.

5.2.3 Estimation Effect Of Database Completeness

The conditional historical data may influence the preciseness of estimation results. The maintenance strategy is mostly based on the historical dataset, so database under condition circumstances may reduce the inspection efficiency greatly. Thus, historical data with different time periods are used to analysis the influence of dataset completeness. Efficient planning is based on the accurate predictions of the sewer system future condition. (Egger et al., 2013). Thus, the accuracy of estimating parameters is studied. The *BSD_MTTF* are estimated from 4 years to 20 years using a synthetic database of 1000 pipes. Figures below show the relationship of estimation value and real value for 5 years, 10 years and 15 years database history.

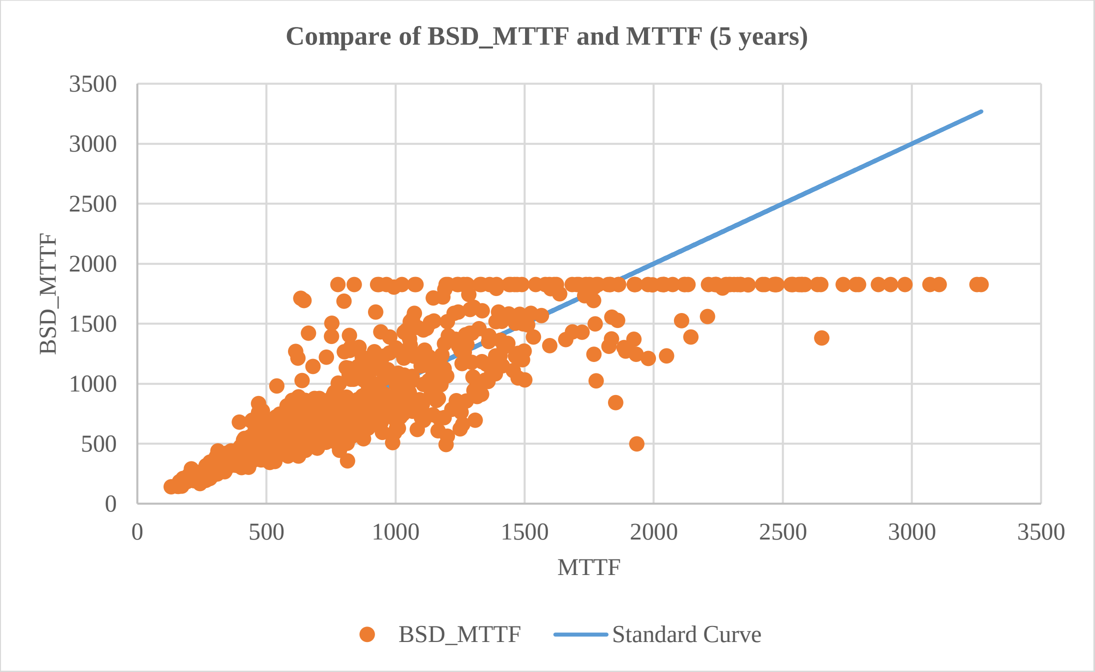

Figure 5-8 Estimate of MTTF from 5 Years Historical Dataset

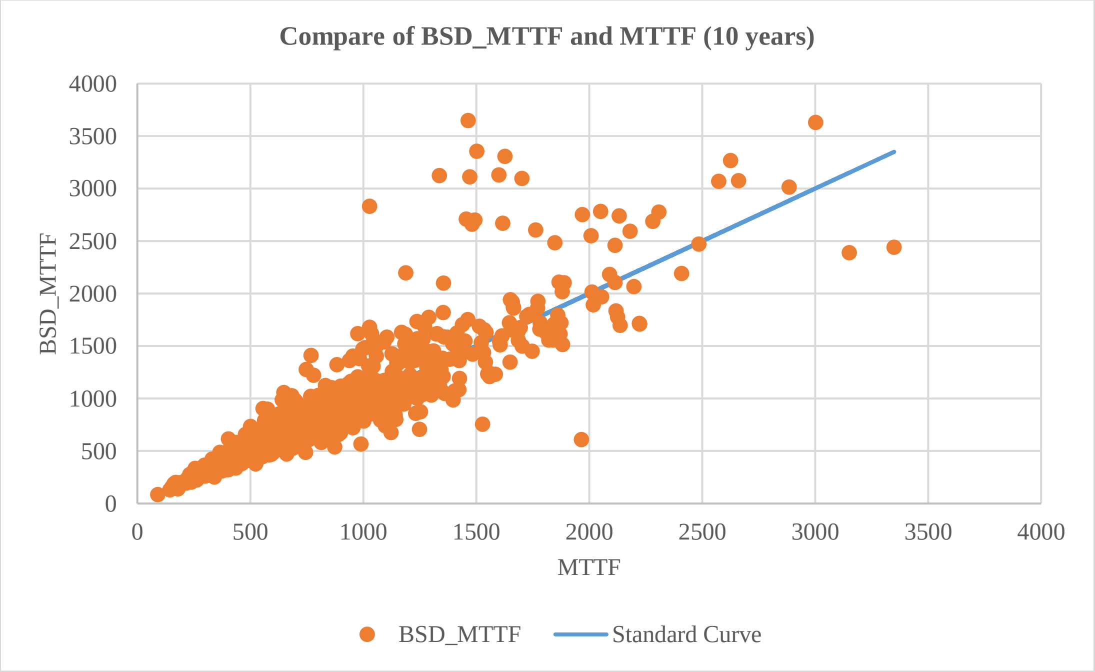

Figure 5-9 Estimate of MTTF from 10 Years Historical Dataset

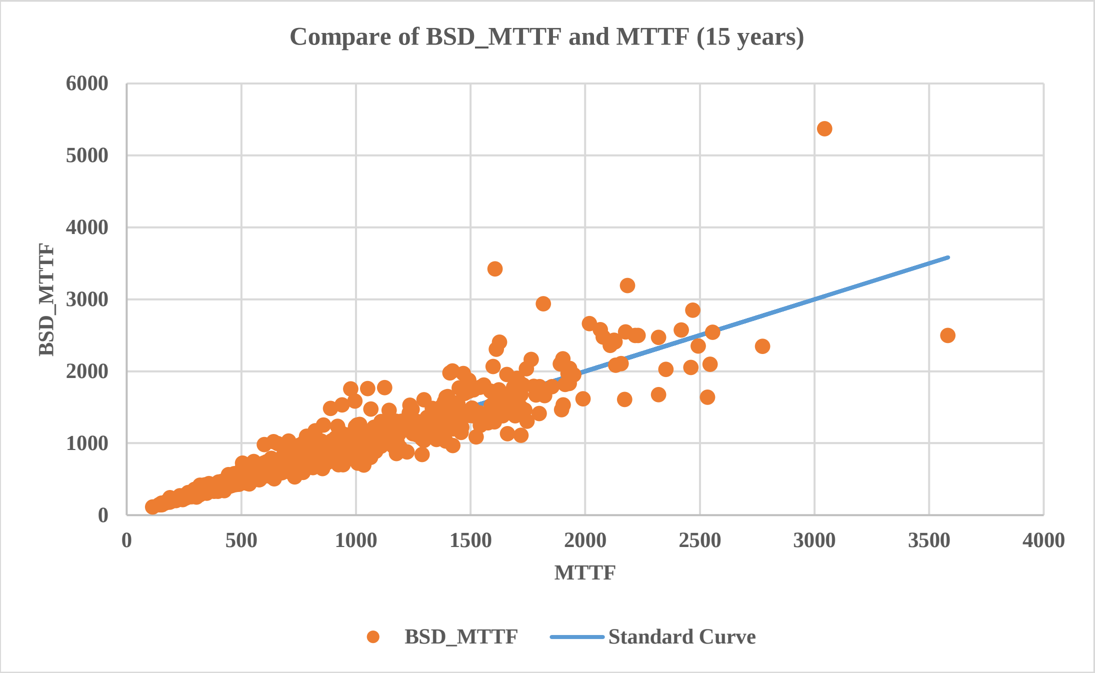

Figure 5-10 Estimate of MTTF from 15 Years Historical Dataset

Analyzing the location of the points compared to the standard curve in the three figures (Figure 5-8, Figure 5-9, Figure 5-10), the points are gathering together and getting closer to the standard curve with the increase of time period, which indicates that with historical dataset of longer time period, the estimation becomes more accurate. Also, R^2 is calculated for *MTTF* data and this is shown in the Table 5-2 and Figure 5-11.

Table 5-2 R^2 Between Estimated and Actual MTTF for Different Historical Dataset Period

Historical Dataset Period (Years)	R^2	
	BSD_Estimation	Median_Estimation
4	0.4948	0.4892
5	0.6606	0.6590
10	0.8013	0.7890
15	0.8755	0.8560
20	0.9215	0.9030

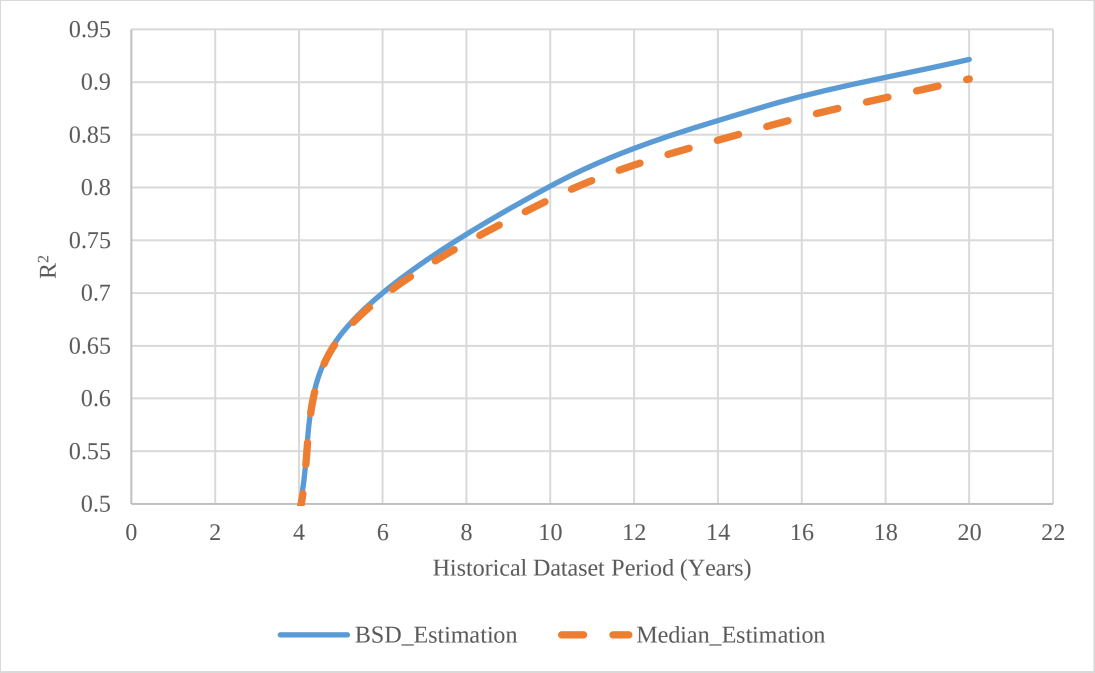

Figure 5-11 Correlation(R^2) Between Estimated and Actual MTTF for Increasing Period of Record

The table and figure shows that R^2 increases with the increase of total time period, which is in coincidence with the conclusion that estimation is more accurate with longer time period. Moreover, with longer time period, the difference between *BSD_MTTF* and *Median_MTTF* is more obvious and utilizing the first method to estimate *MTTF* is of much higher accuracy.

5.3 Inspection Efficiency Analysis

By running the model, the number of blocked pipes in each time period is recorded under three circumstances: without any inspection strategy; with probability-based strategy; with line-by-line strategy. Two methods to estimate parameters are used: BSD estimation method and Median estimation method. The size of the simulated sewer system is 1000 pipes. The length of historical time period is ten years and the length of operating time period is set as two weeks (14 days). Table 5-3, 5-4 and Figure 5-12, 5-13 show how average blocked number changes with the inspected number.

Table 5-3 Average Failure Number Per Time Period (14 days) with BSD Estimation Method

Number of Inspections (pipes/day)	Fail number (pipes/period)	
	Probability-based	Line-by-line
0	22.34	22.34
1	13.18	16.3
2	6.09	10.68
3	1.94	6.97
4	0.8	4.17
5	0.4	2.95
6	0.28	1.98
7	0.17	1.33
8	0.15	1.12
9	0.12	0.92
10	0.09	0.69
11	0.09	0.58
12	0.06	0.51
13	0.07	0.46
14	0.06	0.35
15	0.06	0.38
16	0.06	0.29
17	0.06	0.28
18	0.06	0.26
19	0.05	0.25
20	0.05	0.27

Table 5-4 Average Failure Number Per Period (14 days) with Median Estimation Method

Number of Inspections (pipes/day)	Fail number (pipes/period)	
	Probability-based	Line-by-line
0	22.34	22.34
1	19.27	16.84
2	16.39	11.34
3	13.52	7.35
4	11.27	4.57
5	9.2	2.96
6	7.23	2.07
7	5.87	1.5
8	4.18	1.05
9	3.11	0.78
10	2.12	0.6
11	1.41	0.43
12	0.79	0.46
13	0.46	0.37
14	0.26	0.35
15	0.2	0.3
16	0.18	0.27
17	0.18	0.27
18	0.18	0.26
19	0.16	0.23
20	0.15	0.23

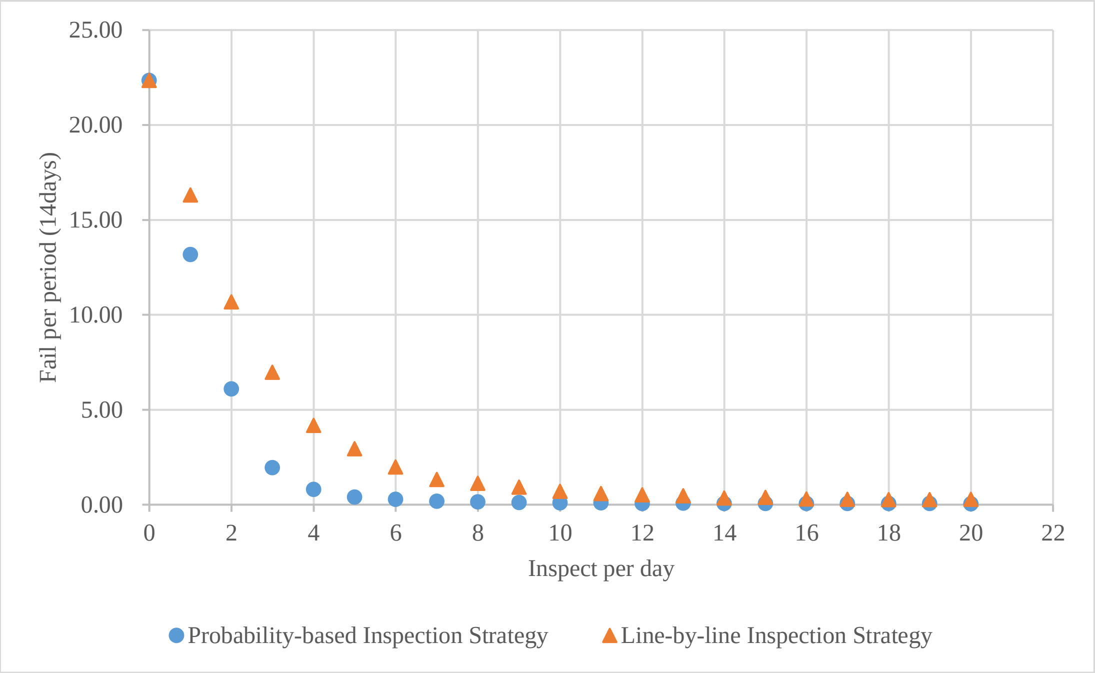

Figure 5-12 Relationship of Number of Failures and Inspections with BSD Estimation Method

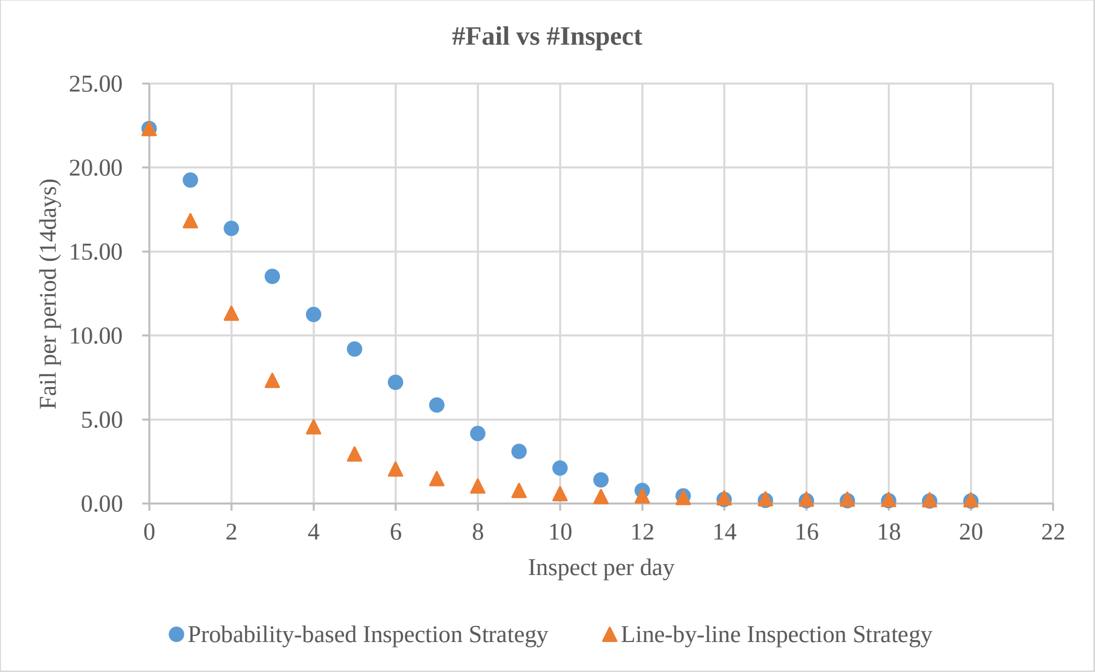

Figure 5-13 Relationship of Number of Failures and Inspections with Median Estimation Method

From Table 5-3, 5-4 and Figure 5-12, 5-13, when number of inspections per day is zero, the points present the condition without any inspection strategy. The number of blocked pipes decreases with the increasing of the number of inspections no matter which pipes are inspected. This results also meet the hypothesis that when more pipes are cleaned, less pipes fail. However, the object of this experiment is try to find out the pipes which need to be cleaned most and to have less failures with the least number of inspections. From this aspect, different inspection strategy and different method to estimate parameters give various results.

In the Figure 5-12, line-by-line inspection strategy always goes higher than probability-based inspection strategy. Probability-based inspection strategy results in only about half of the failure compared with line-by-line inspection strategy when inspecting two pipes a day. When inspecting four pipes per day using probability-based inspection strategy, nearly all the blockages of sewer system have been prevented while when utilizing line-by-line inspection strategy, nine pipes per period is needed to get similar effect. The results show that probability-based inspection strategy is much more successful than line-by-line inspection strategy which indicates the calculation of fail probability is useful.

Figure 5-13 can be interpreted similarly with Figure 5-12. However, the two strategies show completely contrary results. The probability-based inspection strategy is even worse than line-by-line strategy. The reason is that the failure probability calculated in this strategy is imprecise which lead the selection of inspected pipes into a wrong way. This also indicates that $gamma$ matters much in the calculation of failure probability. If the estimation of parameters ($MTTF$ and $gamma$) is not of sufficient accuracy, the probability-based inspection strategy will fail to work efficiently.

Another vital criterion to evaluate the effect of the maintenance strategy is inspection efficiency. This is expressed as the ratio of inspected pipes that will fail without inspection to total pipes that will fail. Inspection efficiency is calculated for the same circumstances described in section 5.2 and the results are shown in Table 5-5,5-6 and Figure 5-14 and 5-15 below.

Table 5-5 Inspection Efficiency with BSD Estimation Method

Inspect percentage of total pipes per period (14 days)	Inspection Efficiency	
	Probability-based	Line-by-line
0.00%	0.00%	0.00%
1.40%	4.89%	1.12%
2.80%	9.49%	3.00%
4.20%	18.18%	6.21%
5.60%	22.39%	7.51%
7.00%	31.58%	9.24%
8.40%	21.74%	12.88%
9.80%	43.59%	15.20%
11.20%	44.12%	19.44%
12.60%	50.00%	13.77%
14.00%	60.00%	18.92%
15.40%	57.14%	18.48%
16.80%	65.22%	20.48%
18.20%	60.87%	22.08%
19.60%	60.00%	22.41%
21.00%	61.90%	18.33%
22.40%	61.90%	17.39%
23.80%	57.89%	12.20%
25.20%	57.89%	15.00%
26.60%	65.00%	17.50%
28.00%	68.42%	12.50%

Table 5-6 Inspection Efficiency with Median Estimation Method

Inspect percentage of total pipes per period (14 days)	Inspection Efficiency	
	Probability-based	Line-by-line
0.00%	0.00%	0.00%
1.40%	0.08%	1.04%
2.80%	0.00%	1.80%
4.20%	0.06%	3.83%
5.60%	0.07%	7.19%
7.00%	0.00%	8.98%
8.40%	0.00%	13.23%
9.80%	0.13%	12.16%
11.20%	0.18%	16.97%
12.60%	0.25%	19.20%
14.00%	0.72%	21.21%
15.40%	1.08%	20.00%
16.80%	4.63%	9.09%
18.20%	6.25%	15.79%
19.60%	17.07%	21.05%
21.00%	21.21%	17.02%
22.40%	25.81%	18.60%
23.80%	23.33%	18.60%
25.20%	20.69%	17.07%
26.60%	25.00%	21.05%
28.00%	25.93%	14.29%

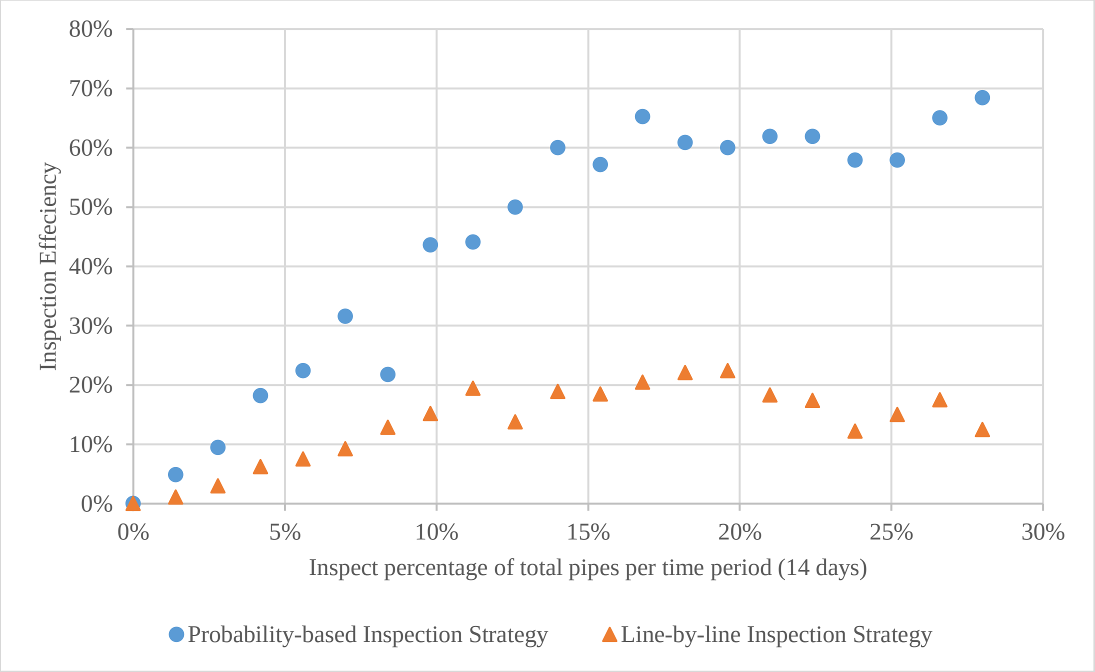

Figure 5-14 Inspection Efficiency with BSD Estimation Method

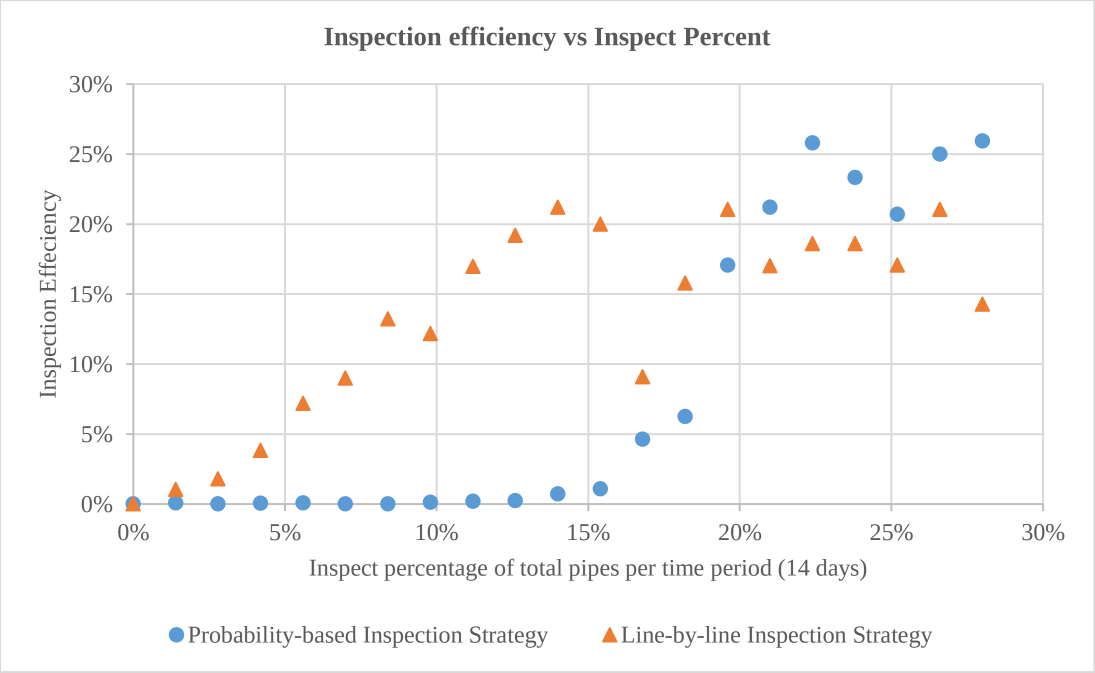

Figure 5-15 Inspection Efficiency with Median Estimation Method

Table 5-5, 5-6 and Figure 5-14, 5-15 above show the inspection efficiency of different inspect percent when utilizing probability-based inspection strategy and line-by-line inspection strategy under both BSD estimation and Median estimation circumstances. These tables and figures show the same results with the analysis of failures and inspect. Probability-based inspection strategy is successful when the estimation is more accurate. In the use of BSD Estimation method, the inspection efficiency could reach 70% which means that 70% of the blockages could be predicted and addressed while when choosing pipes randomly or using inaccurate parameters, the inspection efficiency can only reach 20%.

Two random periods are selected to present the distribution of real blocked pipes and the fail probability of all pipes. See Figure 5-16 below.

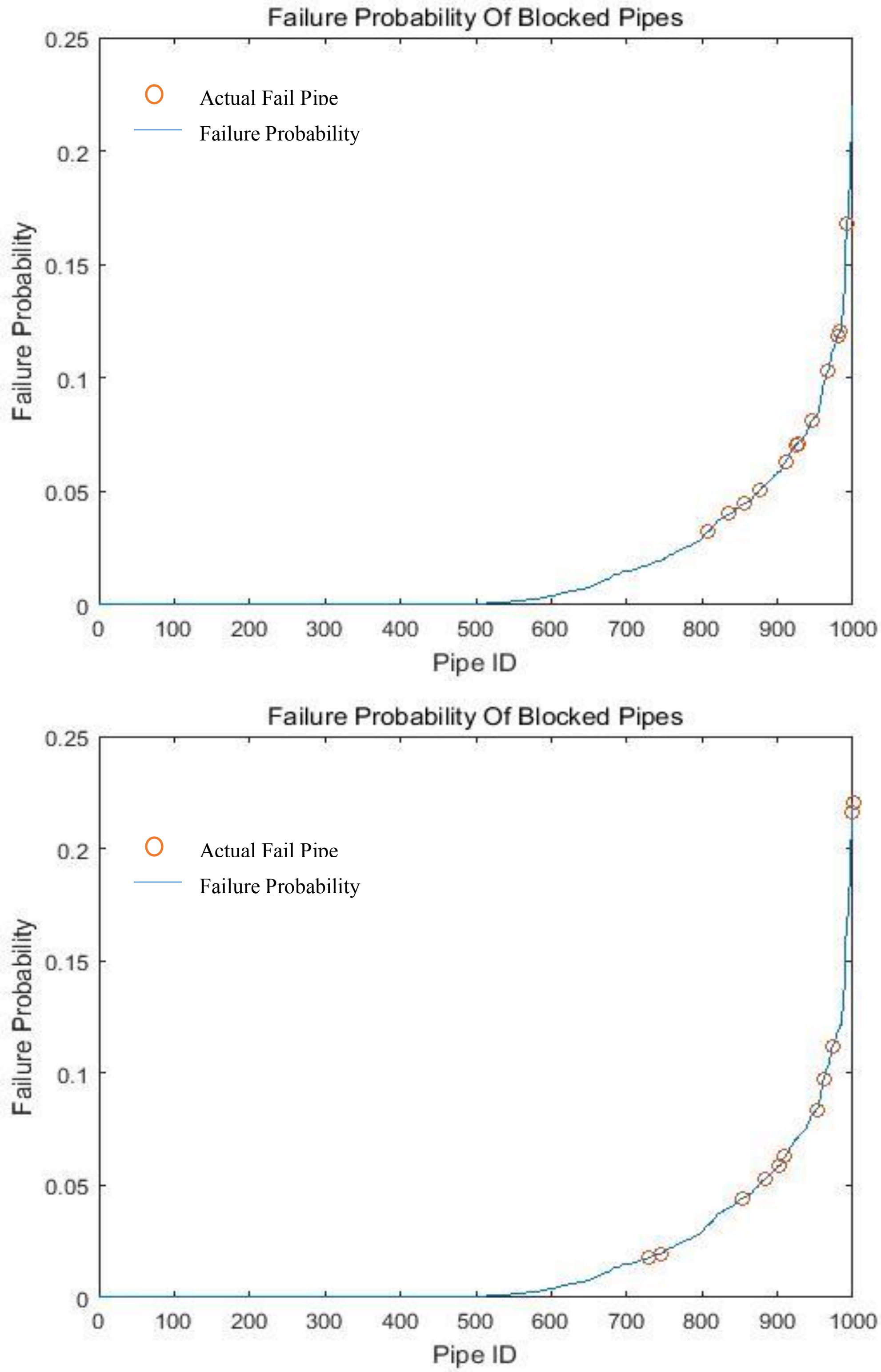

Figure 5-16 Actual Failed Pipes and Failure Probability

The two figures in Figure 5-16 are all for BSD Estimation Method and probability-based inspection strategy, which have the highest inspection efficiency. The blue line in the figure shows the pipes ordered by the fail probability. X axis is the rank of pipes with the ranks corresponding to the predicted failure probabilities in the period. The red circle points show the pipes that actually fail in this time period. In the figure, most of the red circles gather around the high ranking pipes. This also indicates that the probability can orient to the pipes which may fail.

5.4 Optimization of Inspection Investment and Penalties

The capital cost and penalties are analyzed with the most efficient inspection strategy, probability based inspection strategy with BSD estimation method. The ratio of the three parts (inspection cost, cleaning cost and penalty) are calculated with different number of inspections. The size of the sewer system is one thousand pipes. Cost per pipe is set for this condition. To inspect a pipe before it fail, the cost is $75 per pipe. To clean an already blocked pipe, the cost is $185 per pipe and the penalty for this pipe failure is $300. Total duration is 130 weeks (approximately 5 years) and Table 5-7 shows the average cost for each period (14days). Detailed costs are shown Table 5-7 and Figure 5-17.

Table 5-7 Average Inspection, Cleaning and Penalty Costs for 2 weeks

Number of Inspections (pipes/day)	Fail number (pipes/period)	Inspect cost ($)	Clean cost ($)	Penalty ($)	Total cost ($)
0	22.34	0	4132.90	6702.00	10834.90
1	13.18	1050	2437.73	3953.08	7440.81
2	6.09	2100	1127.08	1827.69	5054.77
3	1.94	3150	358.62	581.54	4090.15
4	0.80	4200	148.00	240.00	4588.00
5	0.40	5250	74.00	120.00	5444.00
6	0.28	6300	51.23	83.08	6434.31
7	0.17	7350	31.31	50.77	7432.08
8	0.15	8400	27.04	43.85	8470.88
9	0.12	9450	21.35	34.62	9505.96
10	0.09	10500	17.08	27.69	10544.77
11	0.09	11550	17.08	27.69	11594.77
12	0.06	12600	11.38	18.46	12629.85
13	0.07	13650	12.81	20.77	13683.58
14	0.06	14700	11.38	18.46	14729.85
15	0.06	15750	11.38	18.46	15779.85
16	0.06	16800	11.38	18.46	16829.85
17	0.06	17850	11.38	18.46	17879.85
18	0.06	18900	11.38	18.46	18929.85
19	0.05	19950	9.96	16.15	19976.12
20	0.05	21000	8.54	13.85	21022.38

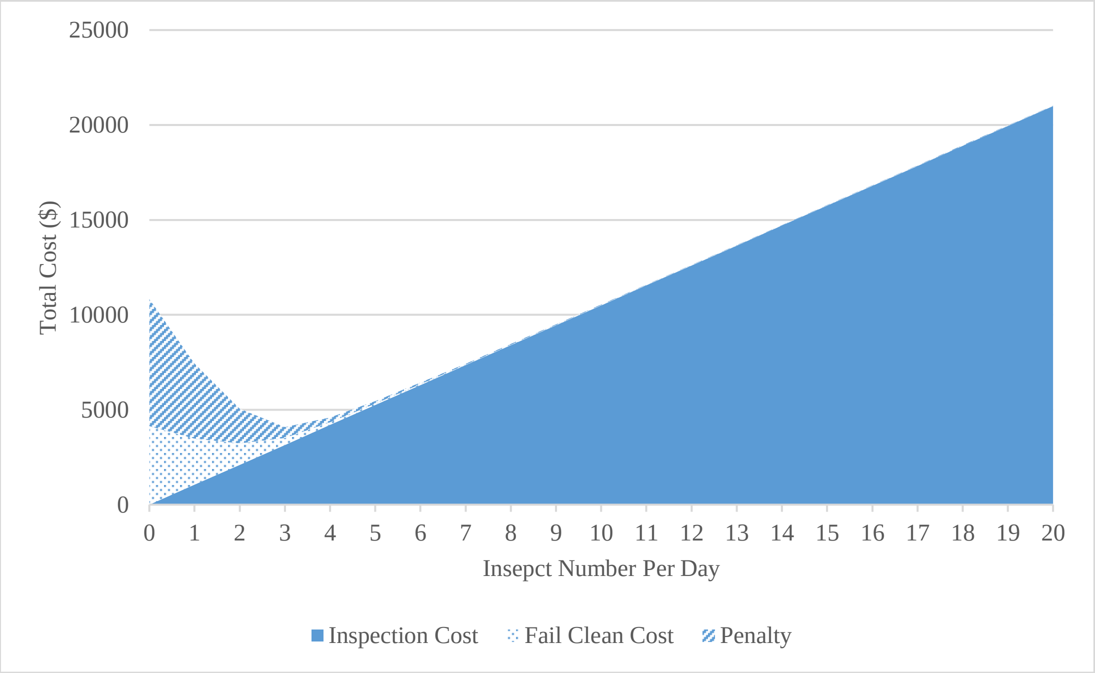

Figure 5-17 Graph showing inspection, cleaning and penalty costs for 14days

Figure 5-17 shows how total cost changes with number of pipes inspected each day. The total cost reaches minimum when about three pipes per day are inspected. This is the rate at which inspection costs increase becomes greater than the rate at which penalties and cleaning costs decrease. Therefore, for the cost structure of this scenario, after this point, inspections costs compose most of the total cost. The ratio of costs also changes with the number of inspections. When inspecting about nine pipes a day, the ratio of penalty and clean cost reach nearly zero which means nearly no pipes fail in this condition. This figure could give some hints about maintenance schedule.

To better express the changing of total cost with various penalties, a larger sewer system is studied. A sewer system comprising ten thousand pipes10 is modeled to compare probability based strategy and line-by-line strategy with number of inspections ranging from 1 to 120 pipes per day, with a total duration of 280 weeks. Average cost for each period (2 weeks) is shown in Figure 5-18. The results also agree with the inspection efficiency comparison. The probability based inspection strategy always cost less than the line-by-line cleaning.

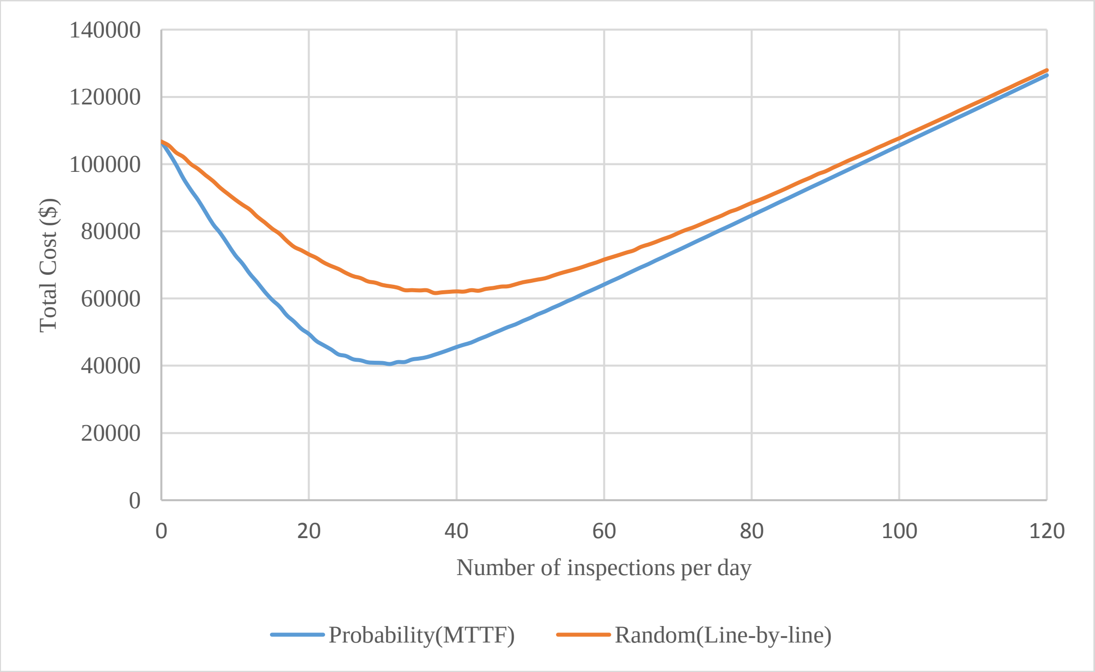

Figure 5-18 Total Cost for 14 Days of Probability-based Strategy and Line-by-line Strategy

From Figure 5-18, given a determined penalty number, there is always a number of inspections per period that provides a minimum total cost. The model will give out how many failures would happen if working with this number of inspections. Consequently, we can draw figures to show the relationship between penalty and failure, penalty and number of inspections under the assumption that the system administrator will seek to minimize total cost. Figure 5-19 and Figure 5-20 indicate these relationships. These two figures can also be utilized to determine appreciate penalty based on acceptable failures per period or inspection capability per day.

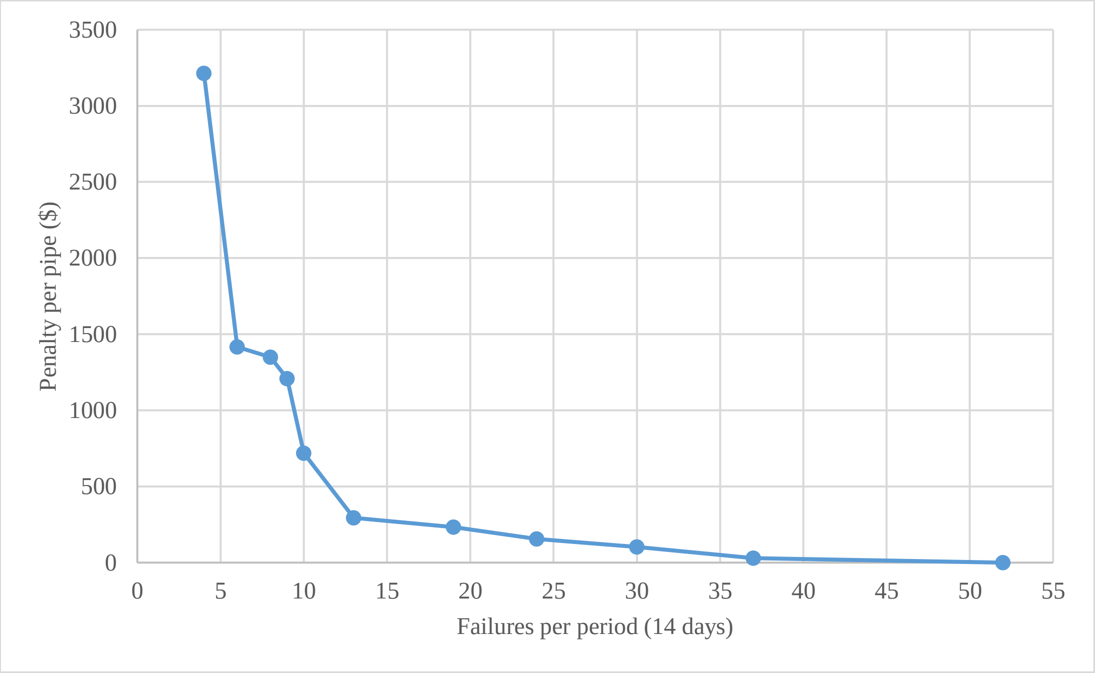

Figure 5-19 Graph Showing Penalties and Failures Based on Minimum Cost

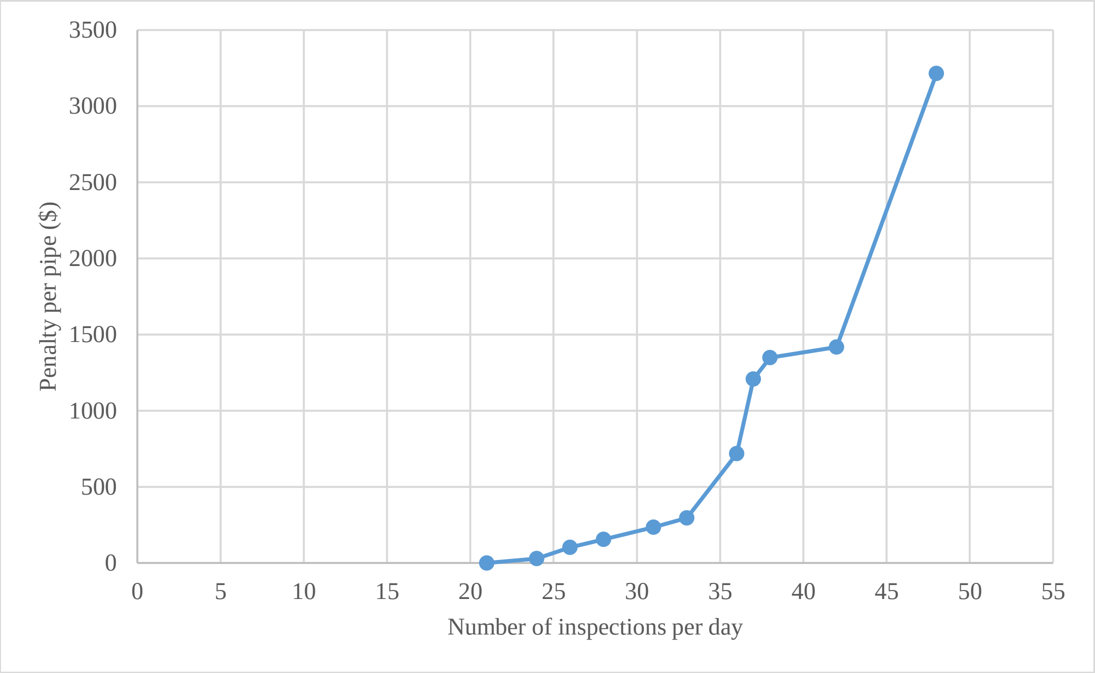

Figure 5-20 Graph Showing Penalties and Number of Inspections Based on Minimum Cost

A more actual way to express inspection capability is number of crews hired which is more convenient for administrations to implement. We change the fixed number of inspections per day to fixed crew number hired. The crews' responsibilities include both cleaning blockages and inspections oriented by the strategy. After analyzing the work load for each crew, we estimate that the cost for crews are $1000 per crew per day. The penalty of $300/pipe failure that was used in the previous simulations is also used in this analysis. Figure5-21, 5-22 and Table 5-8 below show the relations among the number of crew, the number of failures, and the total cost over a period (2 weeks). These figures indicate that regulatory agencies can utilize data about the manpower and equipment costs associated with sewer maintenance to set penalties that can result in minimum total costs coincident with the acceptable failure rate for the system.

Table 5-8 Average Inspection, Cleaning and Penalty Costs for 2 weeks with Increasing Number of Crews

Crew number	Failure number (pipes/period)	Crew cost ($)	Penalty ($)	Total cost ($)
5	218.32	5000	65496.92	70496.92
6	206.44	6000	61931.54	67931.54
7	62.69	7000	18807.69	25807.69
8	24.82	8000	7446.923	15446.92
9	13.88	9000	4163.077	13163.08
10	9.15	10000	2746.154	12746.15
11	6.88	11000	2063.077	13063.08
12	5.05	12000	1513.846	13513.85
13	3.92	13000	1174.615	14174.62
14	3.45	14000	1036.154	15036.15
15	2.77	15000	830.7692	15830.77
16	2.47	16000	740.7692	16740.77
17	2.29	17000	687.6923	17687.69
18	2.02	18000	606.9231	18606.92
19	1.80	19000	540	19540
20	1.65	20000	496.1538	20496.15
21	1.62	21000	486.9231	21486.92
22	1.38	22000	415.3846	22415.38
23	1.37	23000	410.7692	23410.77
24	1.31	24000	392.3077	24392.31
25	1.18	25000	355.3846	25355.38
26	1.15	26000	343.8462	26343.85
27	1.14	27000	341.5385	27341.54
28	1.05	28000	316.1538	28316.15
29	0.95	29000	286.1538	29286.15
30	0.91	30000	272.3077	30272.31

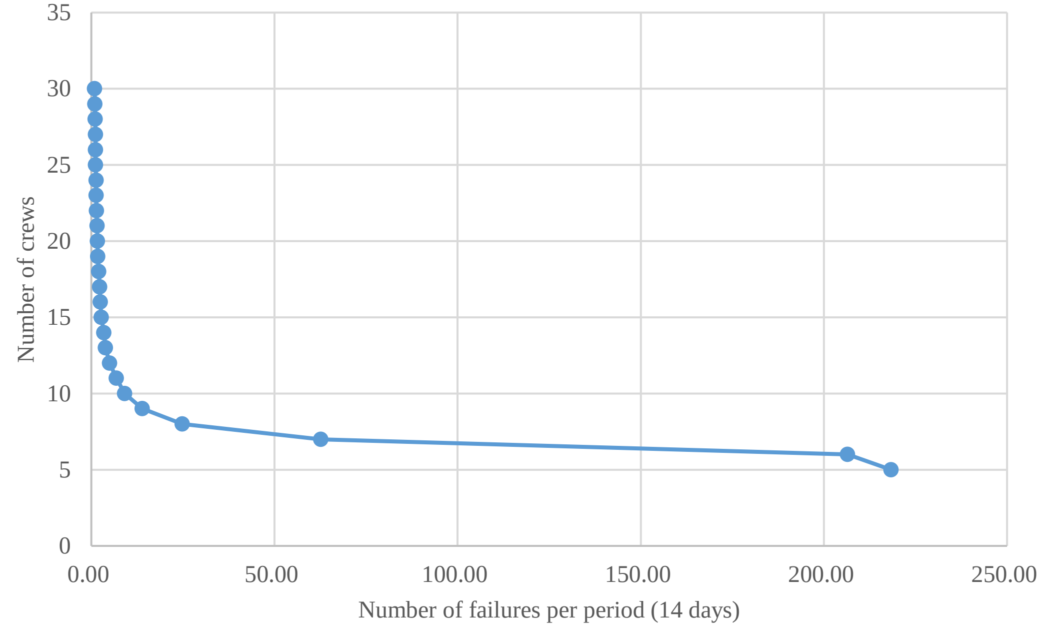

Figure 5-21 Relationship between Number of Crews and Number of Failures

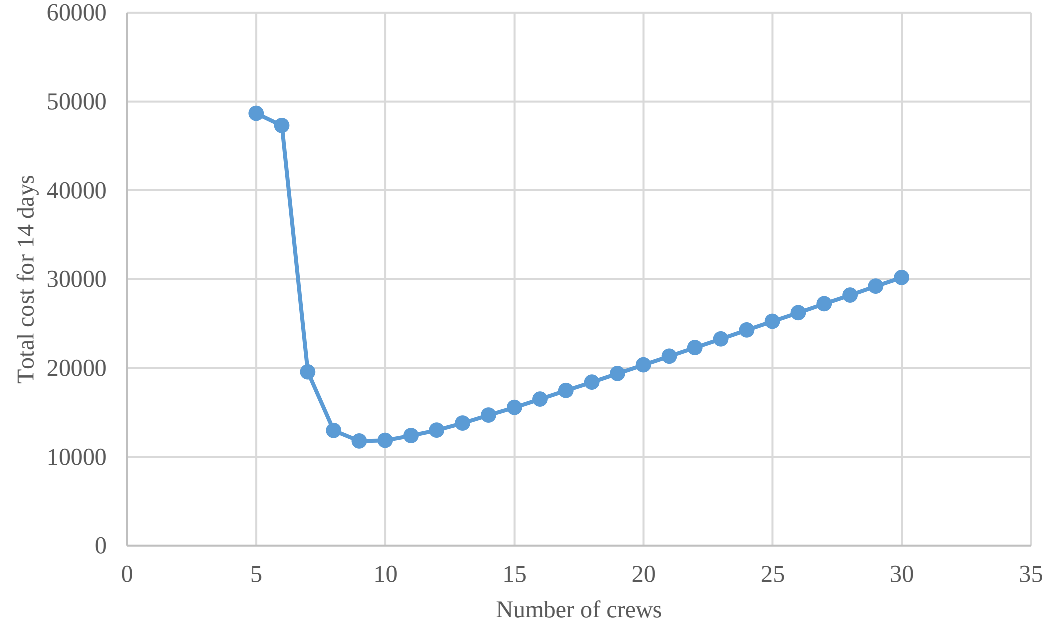

Figure 5-22 Relationship between Total Cost of 14 days and Number of Crews

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

From what we have discussed in Chapter3, 4 and 5, we draw the conclusions below:

- The model developed in this study can be utilized to simulate the operating condition of sewer system with or without inspections strategies.
- Two-parameter Birnbaum-Saunders distribution is utilized to present the interval time between two blockages.
- The two parameters of the model, *MTTF* and *gamma* are estimated from historical dataset use both BSD estimation method and Median estimation method. The BSD estimation method is more accurate but also consume more time.
- Probability-based inspection strategy and line-by-line inspection strategy are compared based on the two estimation method. With high accuracy of parameter estimation, probability-based inspection strategy can successfully reduce the number of sewer line blockages with a given level inspections or reduce the number of inspections needed to attain a give rate of blockages.
- In the economic analysis, probability-based inspection strategy has an obvious advantage over the line-by-line inspection strategy on the capital cost aspect. From

the analyzing of penalty and clean cost ratios, the model provides suggestions of how many crews should be employed based on the given penalties and how to make appreciate penalties based on the acceptable sewer failures.

6.2 Limitation and Future Work

Because long term, pipe-specific records describing failure and inspection of sewer pipes are not available, the model is tested mostly with simulated sewer system which is an ideal condition. Real world implementation still needs to be studied and analyzed. The model needs to be tested with more historical data from different cities.

Though we have developed method to deal with the incompleteness and impreciseness of historical database, we still cannot totally understand how the incompleteness and impreciseness effect the inspection efficiency. The effect of these two factors needs to be studied more in order to improve the inspection efficiency.

In this thesis, for inspections without failure in historical record, we set a particular number (years based on the total length of record) for *MTTF* of this pipe. When data is limited, *MTTF* may be too small that we inspect the pipe too often than needed. This kind of small *MTTF* should be adjust every time pipe is inspected without failure so that its inspection frequency slowly decreases. Over time, all pipes will converge toward the correct *MTTF*. This is not present in this thesis, but need to be considered in future research.

The thesis only provides a simplified method to analysis the costs with crews and fixed hiring investment. More factors such as social impact and environmental influence of sewer failures should be included in the economic analysis parts and need to be studied into details.

REFERENCES

Abraham, D. M., & Wirahadikusumah, R. (1998). Optimization modeling for sewer network management. *Journal Of Construction Engineering & Management, 124*(5), 402.

Ahmadi, M., Cherqui, F., De Massiac, J., & Le Gauffre, P. (2014). Influence of available data on sewer inspection program efficiency. *Urban Water Journal*, *11*(8), 641-656. Available from: Academic Search Complete, Ipswich, MA. Accessed April 14, 2016.

Arthur, S., Crow, H., & Pedezert, L. (2008). Understanding blockage formation in combined sewer networks. *Proceedings Of ICE: Water Management*, *161*(4), 215-221. doi:10.1680/wama.2008.161.4.215

Aziz, T. N., Holt, L. M., Keener, K. M., Groninger, J. W., & Ducoste, J. J. (2011). Performance of Grease Abatement Devices for Removal of Fat, Oil, and Grease. *Journal Of Environmental Engineering, 137*(1), 84-92. doi:10.1061/(ASCE)EE.1943-7870.0000295

Baah, K., Dubey, B., Harvey, R., & McBean, E. (2015). A risk-based approach to sanitary sewer pipe asset management. *Science Of The Total Environment, 505*1011-1017. doi:10.1016/j.scitotenv.2014.10.040

Berardi, L., Giustolisi, O., Savic, D. A., & Kapelan, Z. (2009). An effective multi-objective approach to prioritisation of sewer pipe inspection. *Water Science & Technology*, *60*(4), 841-850.

CEN. (2010). *EN 13508-2/A1. Condition of Sewer Systems Outside of Buildings – Part 2: Coding system for CCTV Inspection*, CEN, Brussels.

CSS, Sewer Drainage, 2013 retrieved from:

http://cssnw.co.uk/products/sewer-drainage/

Del Giudice, G., Padulano, R., & Siciliano, D. (2016). Multivariate probability distribution for sewer system vulnerability assessment under data-limited conditions. Water Science & Technology, 73(4), 751-760. doi:10.2166/wst.2015.546

Duchesne, S., Bouchard, K., Toumbou, B., & Villeneuve, J. (2014). Assessing the impact of renewal scenarios on the global structural state of sewer pipe networks. *Canadian Journal Of Civil Engineering, 41*(8), 761-768. doi:10.1139/cjce-2014-0037

Egger, C., Scheidegger, A., Reichert, P., & Maurer, M. (2013). Sewer deterioration modeling with condition data lacking historical records. *Water Research*, *47*(17), 6762-6779. doi:10.1016/j.watres.2013.09.010

Fuchs-Hanusch, D., Günther, M., Möderl, M., & Muschalla, D. (2015). Cause and effect oriented sewer degradation evaluation to support scheduled inspection planning. *Water Science & Technology*, *72*(7), 1176-1183. doi:10.2166/wst.2015.320

Gemora, I., (2003). Pipeline assessment and certification program. *In: Proceedings of the International Conference on Pipeline Engineering and Construction*, 13-16 July, American Society of Civil Engineers, Baltimore, MA, United States, 822-825.

Hu, Y., Cai, X., & DuPont, B. (2015). Design of a web-based application of the coupled multi-agent system model and environmental model for watershed management analysis using Hadoop. *Environmental Modelling & Software, 70*149-162. doi:10.1016/j.envsoft.2015.04.011

Jin, Y., & Mukherjee, A. (2010). Modeling Blockage Failures in Sewer Systems to Support Maintenance Decision Making. *Journal Of Performance Of Constructed Facilities*, *24*(6), 622-633. doi:10.1061/(ASCE)CF.1943-5509.0000126

Kingman, J. (1993) Poisson process, Oxford University Press, New York.

LANDERS, J. (2013). San Antonio Consent Decree Focuses on Sewer Inspections, Improvements. *Civil Engineering* (08857024), *83*(10), 20.

NYC Environmental Protection. (2013). The State Of The Sewers. retrieved from:

http://www.nyc.gov/html/dep/pdf/reports/state-of-the-sewers-2013.pdf

Møller Rokstad, Marius, and Rita Maria Ugarelli. 2015. "Evaluating the role of deterioration models for condition assessment of sewers." *Journal Of Hydroinformatics* 17, no. 5: 789-804. *Academic Search Complete*, EBSCO*host* (accessed June 11, 2016).

Plihal, H., Kretschmer, F., Bin Ali, M. T., See, C. H., Romanova, A., Horoshenkov, K. V., & Ertl, T. (2016). A novel method for rapid inspection of sewer networks: combining acoustic and optical means. *Urban Water Journal, 13*(1), 3-14. doi:10.1080/1573062X.2015.1076857

Harvey, R. R., & McBean, E. A. (2014). Predicting the structural condition of individual sanitary sewer pipes with random forests. *Canadian Journal Of Civil Engineering, 41*(4), 294-303. doi:10.1139/cjce-2013-0431

Saagi, R., Flores-Alsina, X., Fu, G., Butler, D., Gernaey, K. V., & Jeppsson, U. (2016). Catchment & sewer network simulation model to benchmark control strategies within urban wastewater systems. *Environmental Modelling & Software, 78*16-30. doi:10.1016/j.envsoft.2015.12.013

Salman, B., & Salem, O. (2012). Risk Assessment of Wastewater Collection Lines Using Failure Models and Criticality Ratings. *Journal Of Pipeline Systems Engineering & Practice, 3*(3), 68-76. doi:10.1061/(ASCE)PS.1949-1204.0000100

Sandeep Dominic, C. C., Szakasits, M., Dean, L. O., & Ducoste, J. J. (2013). Understanding the spatial formation and accumulation of fats, oils and grease deposits in the sewer collection system. *Water Science & Technology, 68*(8), 1830-1836. doi:10.2166/wst.2013.428

Sier, D. A., & Lansey, K. (2005). Monitoring sewage networks for sanitary sewer overflows. *Civil Engineering & Environmental Systems, 22*(2), 123-132.

Sumer, D., Gonzalez, J., & Lansey, K. (2007). Real-Time Detection of Sanitary Sewer Overflows Using Neural Networks and Time Series Analysis. *Journal Of Environmental Engineering, 133*(4), 353-363. doi:10.1061/(ASCE)0733-9372(2007)133:4(353)

United States district court, district of Maryland northern division. (2005). Consent Decree - Case 1:05-cv-02028-AMD retrieved from:

https://www.epa.gov/sites/production/files/2013-09/documents/baltimoreco072605-cd.pdf

United States district court, northern district of California. (2014). Consent Decree - Case Nos. C09-00186 and 09-05684 retrieved from:

https://zh.scribd.com/document/263777033/PRR-9015-Consent-Decree-pdf

Wirahadikusumah, R., Abraham, D., Iseley, T.(2001). Challenging issues in modeling deterioration of combined sewers. *J. Infrastruct. Syst., 7*(2), 77-84.