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ASSESSMENT APPROACH TO EVALUATE THE CONDITIONS OF DUCTILE IRON (DI) WATER DISTRIBUTION PIPELINES

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Abstract: As any infrastructure component, watermains are prone to deterioration due to ageing and other influencing factors. Although periodic inspections and renewals are needed, many municipalities confront difficulties in preserving all deteriorated assets due to budget constraints. The use of proper condition assessment, part of asset management, methodologies will enhance the allocation of budgets toward sustainable systems.

This paper developed a desktop analysis scheme that applies to buried Ductile Iron (DI) forcemains to understand the existing condition of watermains. The methodology relied on calculating the residual factor of safety (FoS) that would enable decision-makers in understanding the current structural conditions of the water linear assets. As part of the study, an acoustic inspection tool was used to inspect seven kilometers DI watermains to provide some information about the average remaining wall thickness. A comparison approach between the FoS model and the inspection result was established to understand the difference between the two approaches classification. After categorizing the FoS outputs into three categories using the K-means clustering and establishing a confusion matrix for Good, Moderate, and Poor, the average accuracy was 81%. Besides, the study established a sensitivity analysis and considered the wall loss categorization of municipalities in Quebec by varying the wall thickness with operating pressures in the calculation of the residual FoS. As this study assesses existing conditions of watermains, decision-makers can allocate municipal budgets to avoid catastrophic failure of linear assets.

1 INTRODUCTION

Water networks form a huge infrastructure to supply water to communities. Due to ageing and the environmental exposures, these assets are subjected to deterioration. If not maintained properly, their conditions will drop significantly (Al-Barqawi and Zayed 2006). There are four common reasons that explain the deterioration of linear water assets: 1) the environmental exposure of the assets; 2) limited municipal budgets and changes in municipal priorities; 3) lack of physical inventory and limited resources; and 4) lack of proper maintenance plans and preventive actions (Al-Aghbar 2005). Despite the advancements and technologies, water infrastructure has been deteriorating in many North American cities and municipalities. In Canada, for example, approximately 35% of the linear watermains by length are rated as fair, poor, and very poor. In fact, 15% of these assets are rated as poor and very poor (Canadian Infrastructure Report Card [CIRC] 2016). Additionally, the American Society of Civil Engineers

(ASCE) reported a grade D to the drinking water assets in the United States (US) (ASCE 2017). Such a grade is lower than the overall US infrastructure grade (D+). Approximately, six billion gallons of treated water, in the US, are lost due to deteriorated and leaking pipes. The same report stated that the US water infrastructure experience approximately 240,000 water main break annually. The American Water Works Association (AWWA) claimed the need of at least $1 trillion to upgrade the existing water network to meet the population growth (ASCE 2017).

Therefore, decision-makers need to be aware of the physical inventory they own to properly manage their assets. Besides a comprehensive physical inventory, it is of great significance to understand the existing conditions of the municipal assets to promote preventative maintenance. As municipalities confront limited budgets, it is necessary to design cost-effective intervention plans that aim at maintaining, rehabilitating, or replacing assets. As genuine plans require objective condition assessment activities, which are considered essential inputs for impactful interventions, many models were developed by many researchers to evaluate the existing conditions of watermains. For instance, Yan et al. (2003) designed a model to evaluate the pipe condition based on three levels using a fuzzy multi-criteria decision-making tool. The second level, called “Pipe Physical Factors”, comprised several subfactors in the first level such as pipe age, pipe diameter, and pipe material. The “Environmental Factors” in the second level included three sub factors in the first level were the road loading, soil condition, and environmental surroundings.

Further, Al-Barqawi and Zayed (2006) adopted the Analytic Hierarchy Process (AHP) and the Artificial Neural Network (ANN), which included a set of factors and subfactors, to evaluate watermains. Additionally, El-Chanati (2014) utilized several multi criteria pairwise comparison models including the Fuzzy Analytic Network Process (FANP) to calculate the performance of the water networks. Similarly, Ismaeel (2016) developed a performance assessment model using FANP and PROMETHEE after identifying several water performance indicators extracted from the International Water Association (IWA).

It is true that these models provided approaches to evaluate water networks, they can only be used as a screening approach to evaluate water assets. Relying on asset attribute is essential, yet, similar assets along with their attributes are subjected to variations in the actual exposures (i.e. watermains can have negative structural impacts due to transient pressures). Such variations induce different loadings on the watermain. To study the residual life of water pressure mains, Rajani and Makar (2000) developed a model to estimate the remaining service life of grey cast iron mains. The methodology considered the residual resistance capacity of grey cast iron pipelines, anticipated corrosion rates, and the measurement of corrosion pits to predict the remaining factor of safety (FoS). Despite this significant contribution, this research is dedicated to evaluating grey cast iron, only. Of the ferrous materials, Ductile Iron (DI) pipelines are the widely used assets in the watermains, recently. This is due the following: 1) it requires fewer maintenance requirements; 2) the projected service life can reach to at least 105 years; 3) DI is recyclable material; 4) it withstands severe conditions caused by internal and external pressures (Ductile Iron Pipe Research Association [DIPRA 2019]). Due to its recent applications in the industry, few researchers have been developed to estimate the residual FoS of such material.

This paper’s main objective was to calculate the existing FoS of DI forcemain pipelines considering internal and external pressures along with the remaining wall thickness information. A sample of DI watermains was inspected using an acoustic tool and was evaluated based on the calculated remaining wall thickness. The findings of the inspection were adopted in calculating the FoS, and the K-means clustering technique was utilized to classify the calculated residual FoS values into three groups. These three groups would distinguish Good, Moderate and Poor watermains. The outputs of the residual FoS calculations and the acoustic technology will be compared based on statistical measures. The study considered the standard used by Quebec municipalities also to rank FoS based on varied operating pressures and remaining wall thicknesses. The developed approach can be used as a desktop assessment methodology to evaluate existing DI watermains’ conditions. Therefore, decision-makers can obtain inputs to prioritize watermains for intervention plans.

2 Methodology

The methodology adopted in this research is described in Figure 1. This research reviewed some models that were developed and used as screening tools in asset management. As part of this research, an acoustic-based correlator was used to inspect DI watermains to calculate the average remaining wall thickness. The estimated thickness was then used in the calculation of the internal and external developed stresses. Although Spangler et al. (1973) proposed an equation to calculate the circumferential bending stress in buried pipelines, they did not consider internal pressures developed during operations. Internal pressures are important to be considered as they fluctuate along with the water pipeline network. As the pressure grid varies considerably across the systems, failures occur at higher rates and in shorter time frames where pressures are elevated, and the estimated FoS values against failure are lower. Therefore, the equations developed for the Canadian Energy Pipeline Association (CEPA) by Warman et al. (2009) were used in this analysis to calculate the circumferential (hoop) stress. The equation combines the vertical loads and internal pressure into a single equation for determining the circumferential (hoop) bending stresses due to live and/or soil loads, in addition to internal pressure. These stresses are calculated according to Equations 1 to 2.

[1] $$\sigma_{Hoop} = \frac{3 \cdot K_b \cdot \frac{W\,vertical}{D\,outer} \cdot \left(\frac{D\,outer}{t}\right)^2}{1 + 3 \cdot K_z \cdot \frac{P}{E} \cdot \left(\frac{D\,outer}{t}\right)^3 + 0.0915 \cdot \frac{E\prime}{E} \cdot \left(\frac{D\,outer}{t}\right)^3}$$

[2] $$\sigma_{H\_int\,ernal} = \frac{P \cdot D\,inner}{2 \cdot t}$$

where σ_{Hoop} is the circumferential (hoop) bending stress due to live loads (psi) and dead loads (psi); $\sigma_{H\_int\,ernal}$ is the circumferential (hoop) stress due to internal pressures (psi); D is the pipe diameter; K_b and K_z are soil parameters; t is the wall thickness (in); P is the internal pressure (psi); E is the Young's modulus of elasticity for DI (24x10^6 psi); and E' is the modulus of soil reaction (psi).

Subsequently, the residual FoS is computed after considering yield strength for DI pipe σ_{Yield} (40,000 psi), as per equation 3.

[3] $$FoS_{Residual} = \frac{\sigma_{Yield}}{\sigma_{Hoop}}$$

The calculated residual FoS were grouped into three different clusters in order to compare the results with the acoustic tool. To find the cluster's partitions, K-means technique was utilized. A confusion matrix was established to calculate the accuracy by considering the residual FoS and inspection outputs. A sensitivity analysis was then performed by varying the operating pressure and the remaining wall thickness.

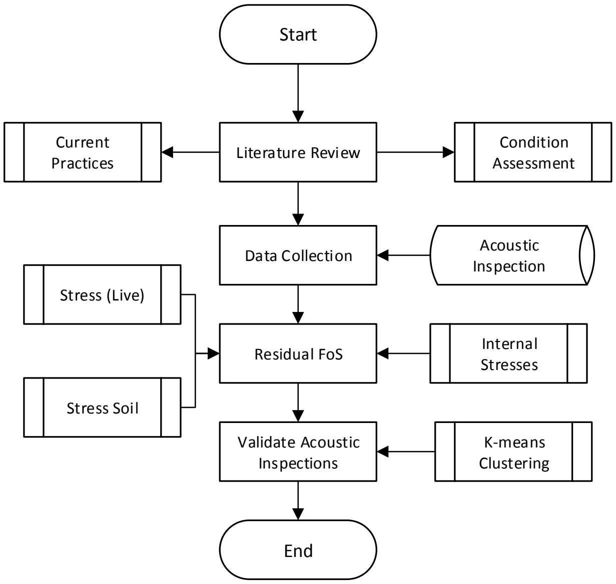

Figure 1: Research methodology

3 Case Study

This research used an acoustic-based inspection tool to assess existing DI in the Norfolk County Ontario Canada, which were constructed in 1991. The acoustic tool can assess ferrous segments (i.e. from the hydrant to hydrant) using an induced noise. The inspection tool provided a calculated average remaining wall thickness along the segment. They are interpreted in the form of three categories, “Good”, “Moderate”, and “Poor”. The categories are correlated to the calculated average wall thickness. A wall loss percentage that is less than 10% is denoted as Good; a wall loss percentage from 10% to 30% is denoted as Moderate; a percentage that is larger than 30% is “Poor”.

The inspected diameter sizes ranged between 8 inches to 12 inches. Nine of the pipelines were 12 inches; 19 were 10 inch, and 25 were 8 inches. The total inspection length was approximately seven kilometers. The resulting inspection outputs are summarized in Table 1. From the table, 12 pipelines were graded as Poor while the majority of the inspected pipelines were graded as Moderate.

Table 1: Inspection Results

Category	12 in	10 in	8 in	Total
Good	1	2	8	11
Moderate	5	9	16	30
Poor	3	8	1	12

The outputs of the inspections have also been evaluated using an accepted classification matrix scheme defined by the Centre D’expertise et de Recherché en Infrastructures Urbaines (CERUI) and used in several Quebec Municipalities. This guide considers five different categories in explaining the condition of a watermain. The dominant criteria to the evaluation and classification of a pipeline are the existing remaining wall thickness of the watermains. Table 2 summarizes the groups that this guide takes into account. The five categories are Excellent, Good “Bon”, Medium “Moyen”, Bad “Mauvais”, and Very Bad “Tres Mauvais”. The same table provides the ranking of the same inspected pipelines. Based on the classification matrix, the majority of the pipelines are categorized as Medium with a grade of 3.

Table 2: CERUI Grading and Inspection Outcome Ranking

CERUI Category	Grade	Wall Loss %	12 in	10 in	8 in	Total
Excellent	1	0	1	0	3	4
Good	2	>0 to 10%	0	2	5	7
Medium	3	> 10% to 40%	6	17	17	40
Bad	4	> 40 % to 70%	2	0	0	2
Very Bad	5	> 70%	0	0	0	0

4 Model Implementation

To use Equations 1 to 2, some practical assumptions and values have to be considered. The Combined H20 live load and dead load plus impact loads, considering six feet cover depth, are approximately 1000 lb/ft^2. Soil parameters are influenced by bedding angle; however, such values were scarce to the authors. Therefore, conservative values were considered in the evaluation in which the assumed bedding angle was taken as 30^0 which is representative of an open trench construction method with relatively unconsolidated backfill such that fully bearing support of the pipe is not achieved. While this is an acceptable conservative value to utilize a newly constructed pipeline, one could argue that as the soil reconsolidates around the pipeline over time, the actual bearing support will be much greater. However, due to the lack of soil information, the authors assumed the aforementioned bedding angle. This corresponds to K_b of 0.235 and K_z of 0.108. Parameter E' is a function of the cover depth (6 feet), soil type, and standard American Association of State Highway and Transportation Officials (AASHTO)'s relative compaction. A conservative value was taken (E' = 1,400 psi) since geotechnical information was unavailable. The assumed value was associated with 95% compaction with fine-grained soil with less than 25% sand content. The operating pressure considered in this evaluation was taken as the pressure rating of these DI pipe class 350 psi. Considering these assumptions, the lower and upper limits of the calculated residual FoS are demonstrated in Table 3. The lowest calculated residual FoS was 2.3; this value was lower than the minimum acceptable FoS for DI design which is 2.5.

Table 3: Residual FoS Results

Residual FoS		Count
Lower Limit	Upper Limit	
2	3	3
3	4	22
4	5	17
5	6	11

5 K-Means Clustering

In an effort to classify the residual FoS into groups, the K-means clustering method was used. K-means clustering technique divides *n* data points into several *k* clusters, by assuming a vector space formation of data points (Zhang and Xia 2009), and finds the centroids of each pre-defined number of clusters. This technique is based on an iterative approach, in which the first iteration relies on randomly assigned clusters to the data point. The result is attained after the solution converges, in which the cluster assignment no longer changes in subsequent iterations. The main steps in applying the K-means clustering technique are summarized as follows:

- Cluster the data based on a pre-defined number of clusters. In this research, the number of clusters is set as three.
- In the first iteration, assign any of the two clusters to the data points as a “random assignment”;
- Calculate the centroid of each cluster, which is the mean of all data points in that cluster;
- Compute the Euclidean distance between each data point and the centroid;
- Assign data points to their closest centroid;
- Repeat steps 3, 4, and five until the solutions converge (clusters are no longer changing for any of the data points);

By implementing such a clustering technique, Table 4 displays the breakpoints between the clusters attained. A calculated residual FoS for any pipeline that is lower than 3.58 will be described as Poor. The same table provides the categorization of the calculated FoS for the different diameters. The majority of the pipelines are categorized as Moderate.

Table 4: K-means Results and FoS Model Outputs Categories

Category	FoS Lower Breakpoints	12 in	10 in	8 in
Poor	0.00	9	2	0
Moderate	3.37	7	18	5
Good	4.36	0	1	11

6 Inspection Validation

Validation is an essential part as it establishes a comparison between actual and estimated outputs. As this model adopted well established and accepted design equations for DI pipelines, the outputs of this model were considered the actual ones when compared to the inspection results’ rankings.

To perform a systematic validation approach, the FoS results were categorized into groups to calculate the accuracy as per Equation 4. This indicator relies on the true positive (TP), true negative (TN), false positive (FP), and false negative (FN).

$$[4]\ Accuracy = \frac{TP + TN}{TP + FP + FN + TN}$$

A comparison between the considered actual against the estimated outputs is shown in Table 5. The table was used to establish a confusion matrix for each category so that the accuracy parameter could be calculated.

Table 5: Actual Versus Predicted

		Actual (FoS)		
	Category	Good	Moderate	Poor
Estimated	Good	9	2	0
	Moderate	9	18	3
	Poor	0	1	11

Upon constructing a confusion matrix for each category, the accuracy parameter was estimated for each category. This would explain the ability of the inspection tool to accurately predict the actual category. The average accuracy was calculated as 81% in which the accuracy for Good was 79%; Moderate was 72%; and Poor was 92%. From the results, the inspection evaluation provided some conservative estimates especially for pipelines that were graded Good in the FoS model but Moderate using the vendor's matrix. Also, the vendor's underestimated the structural performance of some pipelines that were graded as Poor in the FoS model but Moderate in the vendor's matrix. These variations impacted accuracy and classification performances.

7 Sensitivity Analysis

Watermains are designed to withstand internal and external pressures using acceptable FoS. Upon analyzing the potential stresses imposed on watermains, specific thicknesses are selected. Due to environmental exposure and other influencing factors, these watermains will deteriorate. For metallic material, external corrosion could be a result of corrosive soil that forms the envelope of the pipeline. Internal corrosion, however, could be a result of the direct contact of the water medium to the metallic material. The continuous exposure could lead to the reduction in the wall thickness and hence the structural capacity of the metallic pipeline. The impact would increase with the variations of the operating pressures that were not originally considered in the design. Due to the decrease in the wall thickness and increase of operating pressures, the residual FoS will vary.

This research utilized Equations 1 to 3 to calculate the residual FoS by considering the previous assumptions but with varied remaining wall thicknesses and operating pressures for DI nominal sizes of 8 inch, 10 inches, and 12 inches as shown in Figures 2 to 4. The curves and colour coding are based on CERUI (2013) as demonstrated earlier. In general, the graphs suggest that larger DI pipelines have lower residual FoS than smaller DI pipelines at the same operating pressures. This is expected as the calculated stresses are highly impacted by the diameter; bigger diameters are expected to experience larger stresses.

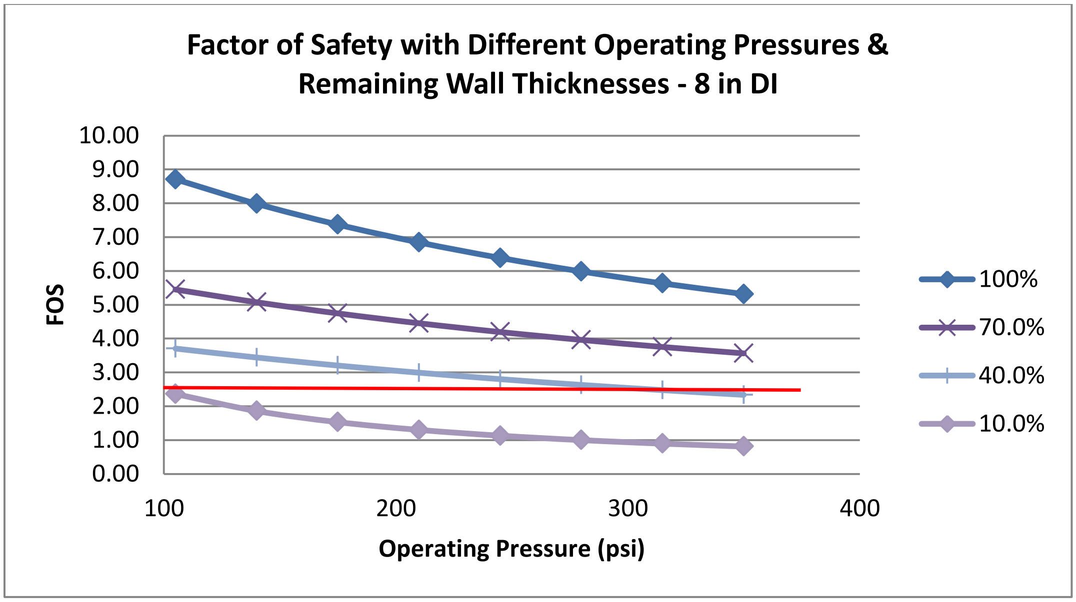

Figure 2: FoS with Varied Operating Pressure and Thickness – 8 in. DI

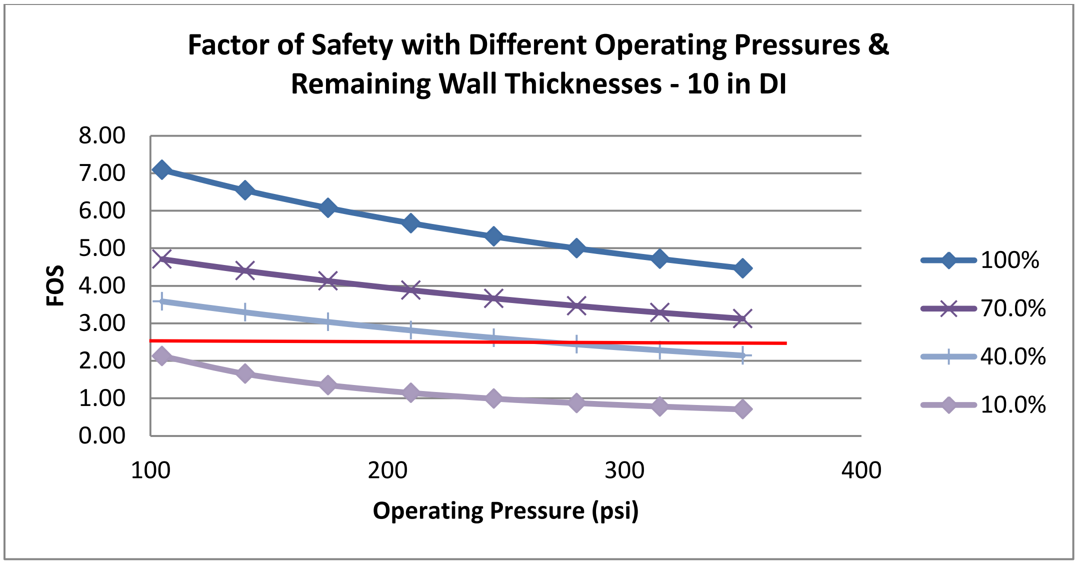

Figure 3: FoS with Varied Operating Pressure and Thickness – 10 in. DI

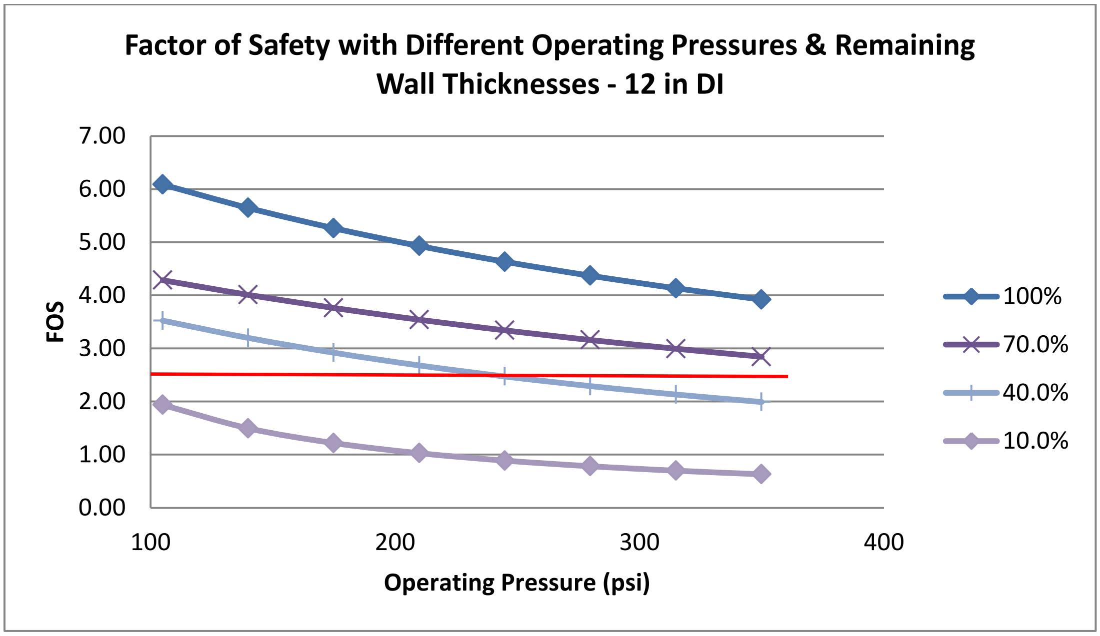

Figure 4: FoS with Varied Operating Pressure and Thickness – 12 in. DI

8 Conclusions

Providing reliable infrastructure is a paramount objective for any municipality. Responding to ageing infrastructure is sometimes costly especially in occasions where pre-planning was not performed. Therefore, it is of great significance to evaluate watermains cost-effectively. It is true that the literature considered evaluating watermains; yet, many of the methodologies relied on decision-making tools that could be beneficial as a preliminary analysis. This paper presented an approach to calculate the residual FoS for DI watermains. The methodology adopted equations to calculate the internal and external pressures along with the yield stress. A case study was used to calculate the FoS for 53 DI pipelines. Subsequently, K-means clustering was utilized to classify the calculated FoS values into three different categories similar to the vendor’s classification. Upon finding the confusion matrices, the accuracy was calculated for each category and on average, it was estimated as 81%. Further, the classification defined by CERUI was adopted to classify the pipelines into five different categories. Based on such a classification, the majority of the pipelines were classified as Medium. After performing a sensitivity analysis by varying the remaining wall thickness with the operating pressure, it was concluded that larger pipelines have lower FoS values than smaller pipelines at similar operating pressures. This conclusion would be applicable to the studied. This model can be used by decision-makers as a desktop analysis tool in evaluating DI watermains in a cost-effective manner. As this model considered some conservative assumptions, municipalities can adjust some of the parameters' values according to actual ones.

9 Acknowledgement

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