A Method for Identification of Pipe Failure Hotspots

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ABSTRACT: This study provides a methodology that can be utilised for identifying pipe sections, which can be considered under high risk of failure. Application of the proposed methodology is demonstrated using a case study involving an in-service large (~1.7 km) critical water main in Sydney, Australia. Geospatial features from Google Earth Pro™ and Google Street View™ were used to assess and quantify typical urban environmental attributes, which can be used for identifying pipe failure hotspot locations. Failure history was used to verify the basis of the methodology developed. It was demonstrated that a sound assessment of the pipe conditions is possible through inexpensive geospatial feature analysis. This development can greatly enhance and reduce costs associated with current pipe condition assessment processes.

KEYWORDS: Pipe failure, Corrosion, Hotspots, Condition assessment, Geospatial platform

1. INTRODUCTION

Water utilities are currently facing major issues with their cast iron pipes that were laid between late 1800 to mid-1900. These issues concern pipe failures, which are now common due to several years of potential coupled stress and corrosion damages (*e.g.*, Xu & Cheng, (2013)). Consequently, most utility boards engage proactively in asset management policies involving pipe condition assessment (PCA) to ensure timely and economical rehabilitation or renewal programs of their asset. Failure of a buried pipe emanating from reduced structural integrity is a complex problem. Identification of at-risk pipe sections near possible failure event and early intervention programs is an essential aspect of critical asset management. The at-risk pipe sections, or hotspots, can be identified either through various properties and features of the native soil environment, the results of (available) pipe condition assessments, or the nature of the soil/pipe interactions.

1.1 Bottom-up approach for pipe condition assessment

Generally, the PCA is conducted at two different levels within a bottom-up approach as summarised in Table 1. This approach reduces the total pipe network area, which can be very large, for assessment to ensure that resources are optimally utilised and detailed assessments are conducted on hotspot sections. The Level 1 PCA generally involves discrete soil sampling along the pipe right-of-way (ROW) followed by their physical and chemical analysis to identify anomalous locations. Resistivity profiling is also common in Level 1 PCA to enable identification of corrosive soil environments (*e.g.*, Deo et al., (2017)).

Table 1 Pipe condition assessment is usually conducted at two different levels involving different investigations

Level	Typical investigations
1	• soil sample collection and analysis. • linear polarisation resistance (LPR) or resistivity profiling
2	• pipe exhumation and visual inspections. • corrosion damage assessment from pit distribution on pipe surface using a non-destructive condition assessment technique. • estimation of remaining life.

Assessments from Level 1 PCA can allow ranking subsections of a pipeline for the next stage Level 2 PCA. In the Level 2 PCA the high ranked, or potential at-risk subsections, are usually chosen for further analysis. The Level 2 PCA stage involves pipe exhumation in order to assess the corrosion damage, which is quantified in terms of the remaining pipe wall thickness. Once Level 2 PCA is completed, the remaining life of the at-risk subsections is then used to prioritise pipe renewal locations. The reader is referred to the work of Rizzo, (2010) for a review of several non-destructive techniques, which can be utilised for PCA.

Successful identification of correct at-risk subsections at the end of the PCA process is highly dependent on the series of process steps undertaken. For illustration purpose, the complete PCA process is conceptualised in Figure 1. Note the reduction in size of the pipe network through each stage. For an efficient PCA process, the initial reduction of the pipe network to a collection of selected pipe sections for Level 1 PCA is very important. This hotspot identification can be achieved through information on failure histories or known age and protection methodologies in place for the sections. Alternatively, the cohort approach developed by Jiang et al., (2017) can be utilised to identify pipes with high possibility of longitudinal fracture. In addition, it is possible to employ statistical or failure data-driven analysis at network level (*e.g.*, Li *et al*., (2014); Lin *et al*., (2015); Chik *et al*., (2017) to screen pipes that require attention for hotspot determination and further Level-based analysis.

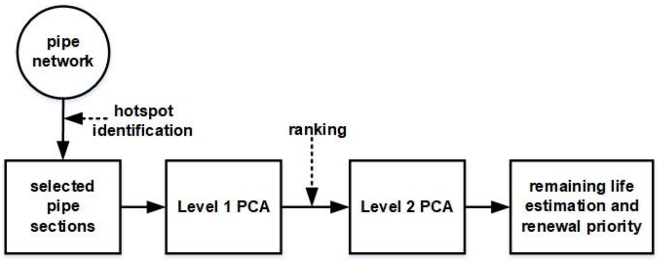

Figure 1 Pipeline condition assessment process leading to lifetime estimation and identification of priority pipes for renewal

1.2 Potential environmental features causing pipe failures

Weerasinghe *et al*., (2017) simulated the influence of reactive soil on small diameter (<300 mm) pipes and noted that the stresses were maximum near certain locations such as driveways (or generally covered area) and tree roots, where the pipes are subjected to differential conditions, and negligibly small in nature strip zones, and away from differential transitions or external influences. Attributing pipe stresses with differential soil conditions, they stipulated that driveways and tree roots, amongst other features, to be important factors contributing to stress related pipe failures. Detrimental effects due to tree root intrusion on non-metallic pipes are well known (see Kuliczkowska & Parka, (2017); Torres *et al*., (2017). Although for metallic pipes tree root intrusion may not be a problem, the presence of trees in close proximity to the pipe and (or) attraction of the roots towards the pipes especially at pipe leak locations due to moisture gradients can restrict pipe movement causing the differential conditions as mentioned by Weerasinghe *et al*., (2017).

The same two features, driveways and trees, can also be associated with providing a conducive environment for pipe material degradation due to corrosion. Azoor *et al*., (2017) studied the corrosion behaviour of a pipe traversing underneath a distinct surface boundary, somewhat simulating the boundary created by a driveway and a nature strip. They noted that deterioration due to corrosion under the covered region (driveway) tends to be higher than that under the natural environment. The cause of this behaviour is differential aeration, which can also be influenced by tree root spreading towards the pipes. Consequently, tree roots can also lead to enhanced degradation of buried pipes due to corrosion.

In summary, the typical urban environment features such as driveways and trees planted along and near to the pipe ROW can contribute towards buried pipe deterioration and failures. Since in strict sense road intersections can also simulate the effects of the driveways and can be considered as transition zones, they can also be considered as potential factors leading to pipe failures. The problem can be significant if the deterioration due to stresses and corrosion are both high due to the subsurface conditions imposed. Therefore, a survey of the driveway and tree features along the pipe ROW can form a practical hotspot identification tool to efficiently classify pipe sections at high risk of failure in huge pipe networks. Although field surveys can provide an accurate assessment of the aforementioned features, it can be impractical considering the size and locations of the pipe network. In this regard, the use of virtual surveys (*e.g*., Berland & Lange, (2017)) utilising readily available geospatial software platforms are very attractive.

The use of satellite imagery has been an invaluable tool for assessment of various features across a spectrum of applications. Applications such as Google Earth Pro™ and the Google Street View™ (GSV) provide a suitable platform for utilities to conduct an initial reduction of their pipe network to selected pipe sections for further Level 1 and Level 2 PCA. This concept formed the basis of the investigation conducted in this study.

However, instead of reducing an entire pipe network, the present work conducted the reduction of a shorter pipe section to identify the hotspots, which can be recommended for Level 1 and Level 2 PCA. The argument for this approach is that if the reduction to hotspots can be achieved on a relatively small pipe section, then the same reduction principle can be applied to the entire pipe network. In this study, we provide a methodology that can provide a reasonable cost-effective approach to the water utilities for identification of potential at-risk pipe sections in the field.

2. METHODOLOGY

2.1 Pipe section for case study

To develop a framework for the work sought in this study, an in-service large (~1.7 km) critical water main in Sydney, Australia belonging to the Sydney Water Corporation (SWC) was analysed. This pipe section (hereafter referred to as SWC12) was constructed in 1954 with cast iron and consists mainly of DN375 and DN450 pipe diameters. The pipe trenches were backfilled with natural soil and the external protection of the pipes was in the form of tar coating provided at the time of installation. Moreover, all pipes were internally cement lined. A few sections underwent added external protection through encasement with polyethylene sleeves in the late 1970's. The SWC12 is within a major suburban location and traverses underneath several built environments (*e.g*., driveways, nature strips, paved roads). Records revealed there were 7 failure incidents in the past decade at different locations over the investigated lengths, with two failures at the same location occurring a few years apart.

2.2 Urban geospatial feature assessment

As part of a different project related to SWC's internal investigation, soil samples were acquired along the SWC12 pipe section. The geographical coordinates for the samples extracted were marked on Google Earth Pro™ to identify the pipe alignment. The soil samples were acquired at ~30 m station intervals except for a few locations, whereby larger steps (50 m or 60 m) steps were used due to the presence of large road intersections. This was inferred after analysis on Google Earth Pro™. The same station spacings were adopted for analysis in this work.

The Google Earth Pro™ platform was used to estimate the width of each individual driveway (W_D) in-between the aforementioned stations along the SWC12 section. The driveways identified were further verified at street level using the GSV feature. From the sum of all driveway lengths ($\sum W_D$) between two consecutive stations, the total length covered by driveways between stations was estimated. There were several cases, whereby relatively large road intersections were present. For these segments, the road width (W_R) was added with $\sum W_D$, since technically roads also simulate the effects of the driveways, *i.e*., causing differential features in aeration and ground movement. The total covered length was then normalised with the station spacing length (S) to compute the Hotspot Density (HSD) as per Eq. 1.

$$\text{HSD} = \frac{\sum W_D + W_R}{S} \tag{1}$$

Note that the term HSD strictly implies segment of the section covered by driveways and road intersections. It is acknowledged here that the HSD so determined are approximations, as an accurate value can only be determined through real field surveys. Nevertheless, random calibrations of driveway widths measured at known locations revealed good estimations.

On the other hand, the total number of trees ($\sum T$) between consecutive stations were counted at the streel level view using GSV as shown in Figure 2. All estimations described were conducted manually without the need for any automated image processing since the length of the SWC12 pipe section was manageable.

Figure 2 Tree counting between stations along the water main was conducted using Google Street View™

3. RESULTS AND DISCUSSION

3.1 Elevation profile and past failure locations

The ground elevation along the SWC12 pipe section is shown in Figure 3. Note, the pipes are assumed to be buried at a nominal depth of ~1 m below the elevation shown. The past 7 pipe approximate failure locations (red shaded regions) are also illustrated in Figure 3 and summarised in Table 2.

From the elevation profile and the failure locations, no strong conclusions can be drawn. However, it is noted that the failures generally occurred nearer to sharp changes in elevation gradients. Failures F4 and F5 occurred near to the elevation troughs along the SWC12 profile. A plausible explanation is that given the groundwater migration pathway follows the natural elevation gradients, the pipe sections at these locations will be exposed to wet soil most of the time. This can lead to a conducive environment for pipe deterioration due to corrosion. However, in the absence of any supporting data related to groundwater migration patterns in the study region, this cannot be confirmed with certainty. Other failures (F1 – F3, and F6 – F7) are observed to have occurred nearer to the elevation crests. These failures, as well as F4 and F5, may be due to stress conditions of the pipes at such locations. Nevertheless, whether the changes in altitude gradients for a pipe's local elevation profile can constitute a potential hotspot location should be investigated further.

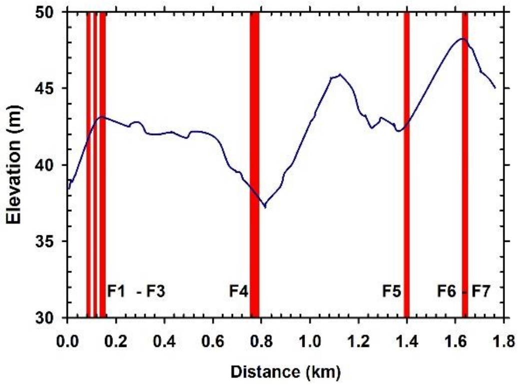

Figure 3 Elevation profile along the SWC12 water main. Approximate past failure locations (F1 – F7) are identified within the red shaded regions.

Table 2 Summary of past failure history. Note the failure locations are approximated between start and end from given address locations

Failure ID	Start location (m)	End location (m)	Failure years
F1	81	94	2013
F2	106	118	2009
F3	132	156	2013
F4	755	789	2003
F5	1391	1411	2016
F6, F7	1628	1652	2007

An interesting feature observed from the failure history is that there were 5 failure episodes that occurred between 2007 - 2013 along the pipe at two clustered locations, which are ~1.5 km apart. Repeated failures at the same locations suggests that the environmental conditions may potentially constitute hotspot locations. Further insights on the failure locations and their connections with the urban environmental features are discussed in the next section.

3.2 Hotspot locations

The hotspot density profile along the SWC12 pipe section is illustrated in Figure 4. Note that the past failure locations presented in Fig. 3 are also shown in Figure 4.

The HSD feature reveals a maximum density of 0.589 along the pipe, which is due to one of the large road intersection (17.2 m) as discussed earlier. The initial ~1 km of the pipe section is along the residential area, while the missing HSD at different locations correspond to absence of housing areas. It is emphasised here that road sections were included in this work, since they can inflict the same effect as driveways; creating artificial boundaries resulting in differential aeration and differential ground movement.

Prior to developing any formative assessment on the connections between the HSD and failures, it is important to note that the former is established after dividing the SWC12 pipe section into certain interval spacings. A change in the interval spacing can lead to some differences in the absolute values of HSD as per Eq. 1. If smaller interval steps are used, then the short length features in HSD will become more noticeable. On the contrary, larger interval steps will tend to dilute the short length variations in HSD. It is emphasised here that the choice of an interval step is highly variable and depending upon the pipe network size can be selected based on the level of reduction required. Nevertheless, upon close inspection and assessment between the HSD and the past failure locations some interesting features are revealed, which are as follows.

From Figure 4, it is noted that the past failures generally coincide with locations, where the HSD ≥ 0.2, except for failures F5, F6, and F7. This HSD limit is adopted after a careful examination of the failures at F1, F2, and F3. In the absence of accurate failure locations, the approximated locations suggest that the HSD = 0.2 can be adopted as a limiting value. Additionally, the nearby failures, F1, F2, F3, are seen to have occurred near one of the highest HSD (~0.578) along the profile. These observations lend credibility to the notion that pipes traversing underneath covered regions such as driveways and road intersections can be vulnerable to failures. Hence, segments of the pipe section with a critical HSD ≥ 0.2 should be immediately considered as hotspot locations. Under this criterion ~660 m of the section (39%) can be considered as hotspots, corresponding to a 61% reduction in the SWC12 pipe section based solely on the HSD analysis.

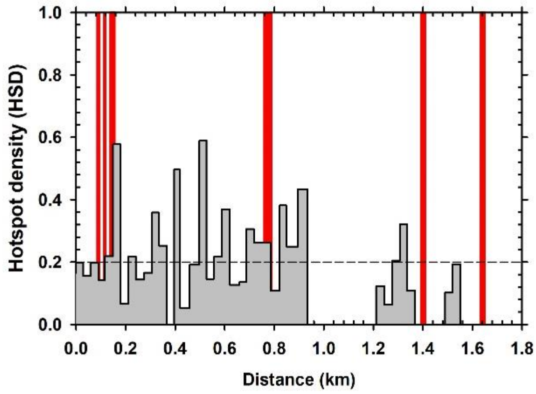

Figure 4 Hotspot density profile along the SWC12 pipe section suggests some association with past failure locations as discussed in the paper

The tree count profile along the SWC12 pipe section is shown in Figure 5. For clarity purposes, the past failure locations are also identified as in Figure 4. Along the pipe, a background count of $\sum T = 1$ amongst stations is noted. Deviations from this ($\sum T > 1$) are seen to generally coincide with the approximated past failure locations (*e.g*., F2, F3, and F4). A notable feature observed during the GSV analysis was that some segments of the pipe sections ran alongside empty fields with large tree coverage. These trees were not incorporated into $\sum T$ since they were farther away from the pipe alignment. However, their sizes suggested that tree root intrusion towards to the pipe was highly possible. The length over which these trees were seen are also identified in Figure 5 as G1 and G2. Interestingly, it is seen that the failure F5 corresponds to location to near one of the dense tree coverage (G2) length.

Given the failure locations (F2 through to F5) reasonably fall near areas of high tree counts and dense tree coverage, these features can be classified as hotspot locations. The length of SWC12 for which $\sum T$ >1 is ~460 m. Similar to the results of HSD analysis, the entire SWC12 pipe section can be reduced by ~73% as hotspot sections based solely on the tree count analysis. However, this interpretation needs to be taken with a level of caution. The analysis here did not account for the tree sizes, which can severely impact their influence on buried pipes. Consequently, locations at which the $\sum T = 1$ can still constitute hotspot locations and their influence will need to be assessed through their actual sizes. Although such quantification can be achieved through real field surveys, automated image analysis from GSV can also be an option for virtual surveys. In this regard, it is noted that automated processing of urban tree features is possible (*e.g*., Branson *et al*., (2018)). However, this is beyond the scope of the work conducted in this paper and should be investigated in future work.

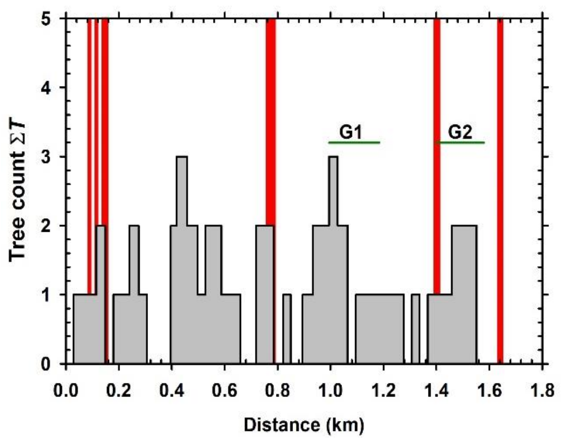

Figure 5 Tree count profile along the SWC12 pipe section with previously identified failure locations. Note G1 and G2 represent dense tree coverage along the indicated length

The combined hotspot sections from the HSD and $\sum T$ analyses ascertained for the SWC12 water main are illustrated in Figure 6. It is noted that 57% (4/7) of the past failures to date have occurred within the hotspot sections. From the combined hotspot sections, it is seen that the entire water main can be reduced by 41% for further Level-based analysis. It is important to deliberate on the absence of any recorded failures at the other combined hotspot sections, especially where large HSD and (or) $\sum T$ were observed in isolated assessments from Figures 4 and 5. There are two possible circumstances to explain such absences. Firstly, these hotspot sections maybe coming to immediate failure conditions and consequently failures at these locations can be expected within a few years. Secondly, the actual soil conditions at these locations may not be corrosive or relatively reactive enough to lead to coupled stress and corrosion induced failures. It shall be noted that there are several influencing factors that can cause failures and the present work is exclusively based on the perspective from typical urban features. If other hotspot identification methodologies (*e.g*., soil sampling and analysis) are integrated with the method advocated in this work, then it is possible to either further reduce (or perhaps increase) the hotspot sections. Such an effort can should be investigated in future studies.

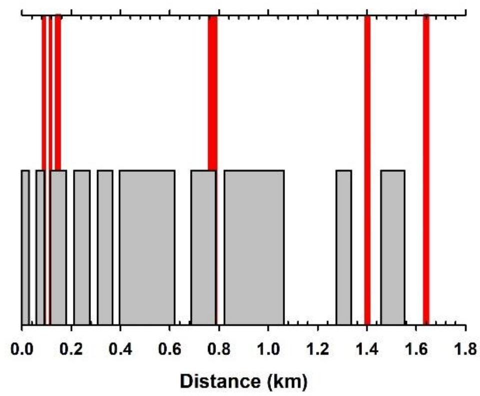

Figure 6 Hotspot sections from the combined analysis of the driveways, road intersections, and tree features along the SWC12 water main compares well with past failures

With the reductions levels possible through analysis of the driveways, road intersections, and trees on the SWC12 pipe section, it is important to reflect the reduction prospect of an entire pipe network. The major concept, as mentioned elsewhere in the paper, is that if the hotspot identification approach can reduce a pipe section into short selected subsections, where pipes maybe at high risk of failure, then the same reduction principle will be applicable to entire pipe networks. The reduction possibility demonstrated for the analysed pipe section has high attraction for large pipe networks, which can be very difficult to manage as part of asset management processes. However, it is acknowledged here that the actual reduction levels possible will vary amongst different networks, depending upon the collection of environmental attributes suggested as pipe deterioration signatures. Notwithstanding this, an encapsulated procedural framework can now be formulated.

3.3 Proposed methodology for hotspot identification

With the systematic analysis procedure adopted in this study and the observed results, a methodology can now be specified to allow reduction of the pipe network sizes through hotspot identification as desired in Fig. 1. This methodology is presented in Figure 7 with the detailed reduction process summarised within the dashed box. For an efficient hotspot identification process, it is desirable to have failure history within the network in order to permit calibration of important parameters (*e.g*., critical HSD). This would allow network specific reductions to be conducted. Nevertheless, even in the absence of failure histories, a critical HSD can be adopted by gleaning through the distribution of HSD present in the dataset.

It is emphasised here that the purpose of hotspot identification is not to identify exact pipe failure locations. It is rather to identify segments within a network or a section, where potential failure is expected so that the next step involving Level 1 PCA can be strategically focussed on those locations (see Figure 1). The basis for the reduction methodology or the hotspot identification methodology is that typical urban environmental attributes such as driveways, road intersections, and trees can provide a favourable environment for pipe deterioration through stresses and corrosion. In this context, it is highlighted that some of the hotspots identified through the reduction process in Figure 6 maybe due to stress, or corrosion, or a combination of stress and corrosion, *i.e*., an identification of the predominant deterioration mechanism cannot be conducted within the hotspot identification methodology. Nevertheless, this is not an important requirement within this stage.

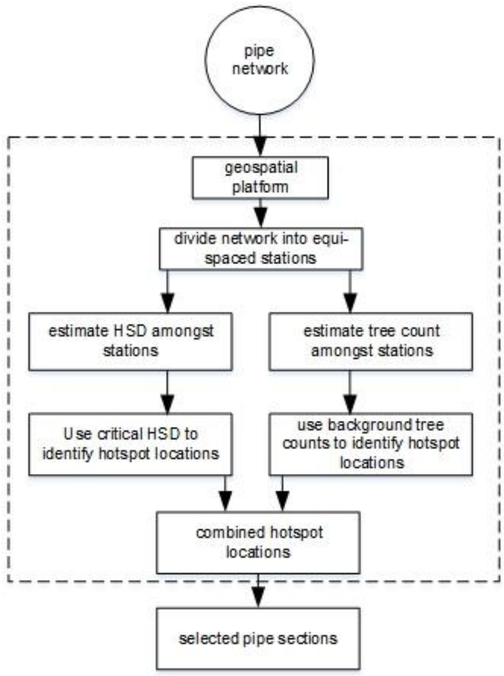

Figure 7 Proposed methodology for reducing pipe network to selected pipe sections through hotspot identification. The series of procedures enveloped within the dashed box can be utilised for size reduction.

With further strategic data collection, more environmental attributes can be identified and incorporated to advance the hotspot analysis proposed in this work. For example, if water pressure becomes excessive due to topological depressions resulting in deeper pipe depths (*e.g*., for gravity-controlled pipes) or pressure transients are more likely due to some operating conditions, then they can also be added to the hotspot analysis. Another potential condition, which has not been investigated in this study, is the consequence hotspot. This classification concerns attributes that can be significantly and drastically affected in case of a pipe failure leading to flooding conditions. Consequence hotspots are therefore associated with locations offering critical service (*e.g*., hospitals and medical facilities) or that are susceptible to flood induced damages. It is noted here that the incorporation of consequence hotspots within the hotspot identification frame of work is important and can be pursued in future.

Although driveway induced stresses may not be a major factor for large diameter pipes (>300 mm), the environmental attributes assessed can lead to enhanced corrosion activities, which can lead to pipe failures. Within this argument, it is clear that differential aeration maybe an important factor leading to corrosion induced failure of large diameter pipes. Given the complexities with corrosion in the soil environment and the dynamicity of the participating environmental variables (see Deo *et al*., (2014)), it is interesting to note that the quantification of urban environmental features, which have a scientific basis for causality, can provide indications of potential pipe failure locations as demonstrated through comparison with failure data.

An important demonstration within the proposed methodology is that open source geospatial platforms such as Google Earth Pro™ and GSV can be utilised inexpensively and with ease for the network reduction process, eliminating any sophisticated procedures and expensive platforms. This serves as highly attractive to small-scale water utilities with constrained capital expenditure for PCA programs since it allows them to screen their asset in a simple manner. Importantly, the hotspot analysis can be used even when reliable past failure data are not available as is the case with some smaller utilities. When failure data are available, it is possible to combine the data-driven analysis with hotspot analysis to enhance the selection of pipes for Level 1 PCA. However, the development of this combined approach requires further research.

3.4 Limitations and future work

From the discourse presented in this work, it is obvious that the methodology will provide a practical and timely tool for water utilities as part of their PCA process. However, it is duly noted that in the present work a manual assessment on the Google Earth Pro™ and GSV platform was undertaken since the size of the pipe section was manageable. For the methodology to be applied on large pipe networks, it is highly recommended that a methodology for automated processing of images from GSV is developed that incorporates the series of processes summarised in Fig. 5. Manual assessment on large pipe networks can be highly improbable, albeit it can still be applied to a reasonable network size.

Furthermore, the basis of the methodology is only applicable to network locations in urban type settings. For sections of the network located in empty rural locations, which are absent of driveways and (or) tree coverage, alternative hotspot identification methodologies are needed and these should be developed in future.

One of the striking observations from this work is that that appears to be a critical HSD that can act as a potential signature of pipe failure locations. From the analysis herein, this critical HSD was determined to be 0.2. It would be highly advantageous to utilise the methodology from this paper to study other pipe sections and investigate whether such a critical HSD does indeed exist. If it does, then a re-look at current guidelines for installing pipes in urban locality would need to be considered. Similar comments are also applicable to the current practice of planting and selection of trees along nature strips.

Moreover, a validation of the hotspots identified for the pipe section studied in this work would provide an indication on the efficacy of the proposed methodology. Comparison of actual pipe conditions within the hotspots and coldspots would be beneficial in this context. Nevertheless, it should be realised that hotspot identification does not need to be exactly accurate in identifying at-risk pipe sections. It serves as a mediatory within the complete PCA process. The task of identifying actual locations of at-risk pipe sections is through Level 1 and Level 2 PCA and therefore this distinction should be maintained.

4. CONCLUSION

Systematic pipe condition assessment program conducted by water utilities is an important asset management process. However, depending upon the pipe network size and its locality, most utilities may not be able to perform the PCA process over a larger section of their network, especially when reliable past failure data are not available. In order to reduce the network size for Level-based analysis and to ensure that potential pipe failure locations are included in the reduced size, an initial hotspot identification methodology is warranted. In this work, we have provided an inexpensive solution utilising the Google Earth Pro™ and Google Street View™ geospatial platforms. Through an assessment and quantification of typical urban environmental attributes that can be influential for pipe deterioration through mechanical stresses and corrosion enhancement due to differential aeration, it was shown that a typical pipe section could be reduced by 41% for further Level 1 and Level 2 PCA. This reduction was of course possible through characteristics observed between driveways, road intersections, and tree distributions along the pipe section, which are typical in urban locations. Nevertheless, if similar reductions can be achieved on large pipe network sizes, it can result in significant improvements in cost and time associated with better management of large asset infrastructure. We believe this is the first time such a demonstration is presented for efficient management of pipe asset. It is expected that the developments from this work will be highly beneficial for water utilities for efficient management of their asset in field. Furthermore, research can be undertaken to advance this method further by strategically recording the accurate locations of pipe failures (with the use of advanced GPS devices) and identifying other environmental attributes for hotspot analysis. Automation of the methodology will greatly assist network level analysis. Finally, it is also possible to incorporate this methodology into either data driven or mechanistic failure prediction methods to improve likelihood of pipe failure for screening pipes for renewal.

5. ACKNOWLEDGEMENT

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