CORRELATION OF PIPE FAILURES WITH PRESSURE AND GROUND MOVEMENT IN AUCKLAND'S WATER DISTRIBUTION NETWORK

L. Lopez, J.E. van Zyl and B. Harkness

ABSTRACT

As part of Watercare's ongoing water network optimisation, this analysis geospatially associated 6 years of reported watermain failures in Auckland's metropolitan distribution network with pressure from hydraulic models, and with ground movement data derived from the Sentinel-1 satellite radar system.

As expected, overall results identified positive correlations between maximum pressure and general watermain failures. Asbestos cement pipe showed consistent pressure-failure trends irrespective of diameter, however polyethylene showed a notable failure increase as the diameter decreases. Pressure-failure rates in PVC also rise with pressure but marginally reduce with smaller pipe diameters.

Next, the quantity and intensity of ground movement represented by four key criteria from satellite data was spatially related to failed pipes and against comparable intact pipes during the same 5-month lead-up to failure. The purpose was to determine whether this indicator of accumulated ground movement could be correlated with reported failures. Results, however, suggest no significant difference between ground movement as related to reported failed pipes and intact pipes, although a survival bias is acknowledged due to subsequent physical changes in the reflecting surface above or near the repair site.

In summary, this pressure-failure analysis supports wider business initiatives to reduce pressure in areas of the distribution network, but further work is required to associate ground movement indicators with watermain failures.

KEYWORDS

Pipe failure, pressure, ground movement, satellite, deterioration

PRESENTER PROFILE

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1 INTRODUCTION

Understanding the influence of factors involved in water pipe failures is fundamental to optimise the limited pipe repair/replacement budgets available to utilities. While literature demonstrates considerable efforts to understand correlation between failures and factors such as pipe material (Alvisi & Franchini, 2009; S. Christodoulou et al., 2009), age (Kao & Li, 2007; Kleiner et al., 1998), corrosion (Johnson et al., 2007; Rajani & Kleiner, 2001) and soil properties (Kleiner & Rajani, 2010), few studies have analysed wider correlations such as network pressure or ground movement with pipe failures.

Network pressure is widely recognised as a major contributor to both leakage rates (Cassa et al., 2010; van Zyl & Cassa, 2014) and pipe failure frequency (Akbarkhiavi & Imteaz, 2020) in water distribution systems. While many studies have shown that pressure management reduces failure rates in a given pressure zone (Lambert & Thornton, 2011), evidence of the correlation between failure rate and pressure within various zones in the same distribution system is lacking. Therefore, the first part of this study analysed the impact of modelled pressure on the failure rates of different pipe diameters and materials in Auckland's water distribution network.

Anecdotally, seasonal changes in soil moisture contributes to ground movement which can affect instances of reported leaks in the Auckland region so the second part of the study investigated any correlation between reported failure events and indication of ground movement obtained from satellite radar measurement. To evaluate this effect, the ground movement data of failed pipes and equivalent intact pipes were compared for a given period before each recorded failure event.

The base data of the analyses is described in the next section, followed by the discussions of each part of the study, including their methodology and results. Finally, the general conclusions of the study are discussed.

2 DATA ANALYSIS

All data included in this study was provided by Auckland's water utility Watercare Services Limited (WSL). The data was received in four separate data sets, which are described below.

2.1 WATER PIPES GIS

The WSL Water pipes dataset contains information on the water distribution system pipes, including attributes as length, status (e.g. "Abandoned", "In Service"), diameter, material, installation date and assigned process (e.g. "Distribution", "Service line"). The total dataset includes 10,479 km of water pipes, the extent of which is shown in Figure 1.

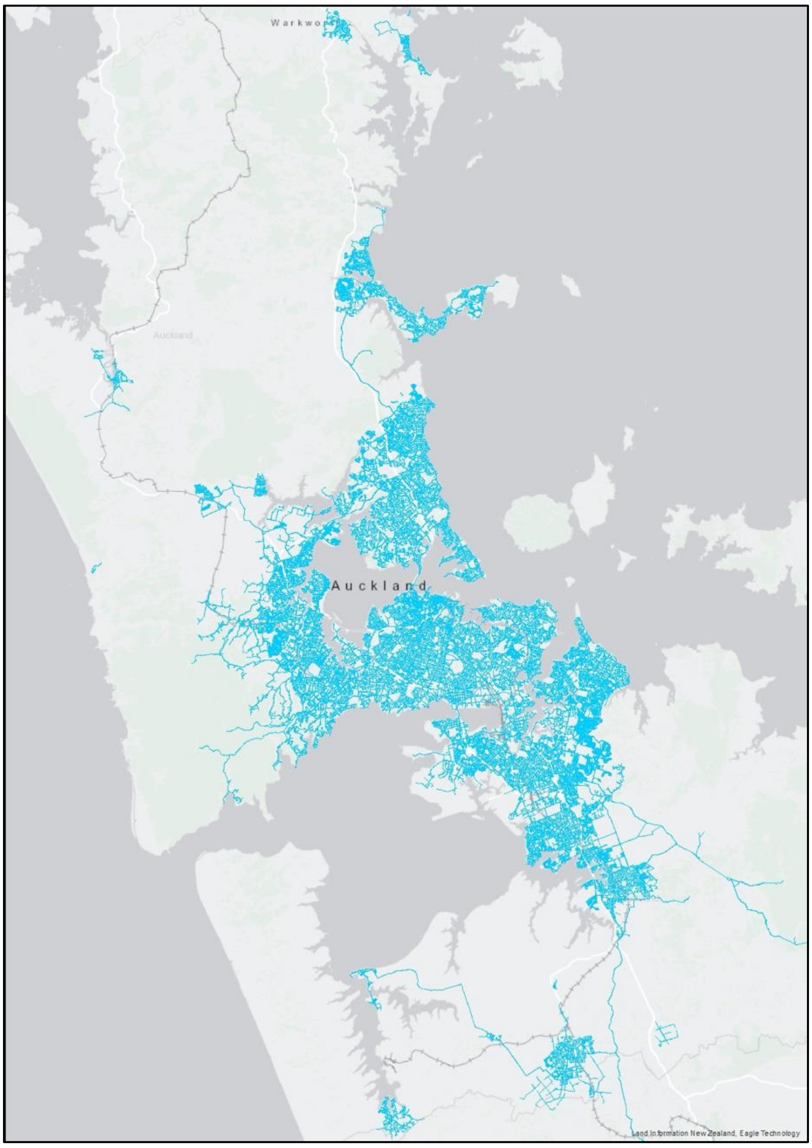

Figure 1: Auckland's water supply network.

Auckland's water supply network has approximately 8,872 km of (local network) water distribution pipes in-service, excluding the bulk network, customer service lines and abandoned or removed pipes. Asset data shows the pipe material distribution to be approximately 32% asbestos cement (AC), 28% polyethylene (PE), 25% PVC and 5% cast iron (CI). Regarding pipe diameter, 28% are smaller than 50mm, 37% are between 50 and 100mm, 20% between 100 and 150mm, 8% between 150 and 200mm and 5% are larger than 200mm. Figure 2 illustrates the distribution of pipe material in each diameter range. The graph shows predominately polymer material in the smaller diameters. On the other hand, AC is the predominant material in the most common diameter range (50-100mm).

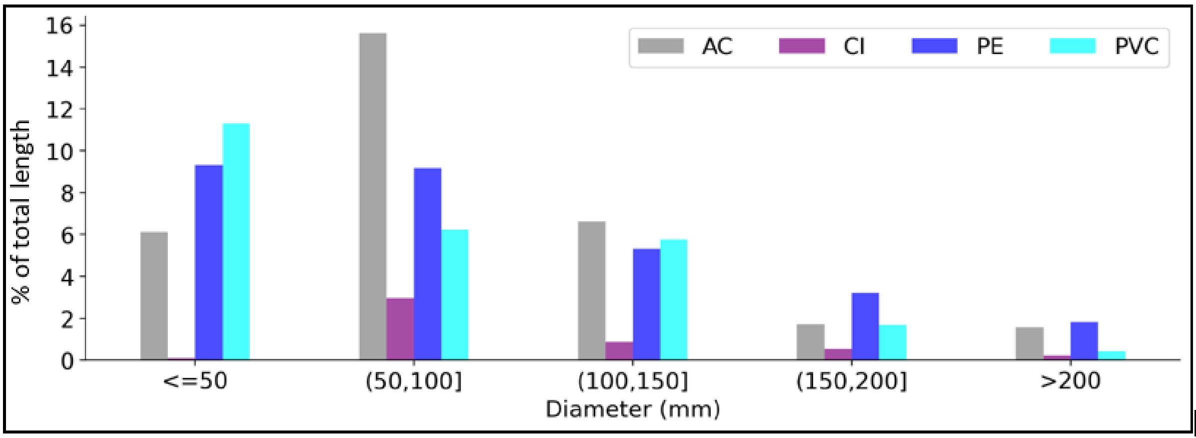

Figure 2: Material profile in Auckland's water supply network.

2.2 HISTORICAL SERVICE ACTIVITIES

Asset maintenance data provides details of more than 590,000 service activities related to failures in Auckland's water and wastewater networks from January 2014 to December 2019. From this data, a water pipe failure events dataset with 13,057 records were extracted, including repair date and pipe id as attributes. A failure has been defined as any repair or replacement activity enacted on a main water pipe as a response to a user reported leak, excluding third-party damage. In this data set, the distribution of materials is 46% AC, 25% PVC, 15% PE and 5% CI.

The pipe failures were later integrated into the network dataset by adding the attribute "Number of failures". Hence, based on the material's total length, a failure rate in failures/km/year was derived. The failure rate of the different materials was found to be 0.318 failures/km/year for AC, 0.228 failures/km/year for PVC, 0.214 failures/km/year for CI, and 0.123 failures/km/year for PE.

2.3 PRESSURE NODES

The pressure dataset included 175,138 geolocated pressure nodes from network hydraulic models of various currency and confidence levels. The attribute table reported the maximum and minimum pressure values under peak demand conditions. Figure 3: Distribution of maximum modelled pressure in Auckland's water distribution network Figure 3 shows the spatial distribution of maximum pressures in the Auckland water distribution network. The maximum pressures can be observed to follow the topography in many cases, with a concentration of high maximum pressures in the south-east region of the city.

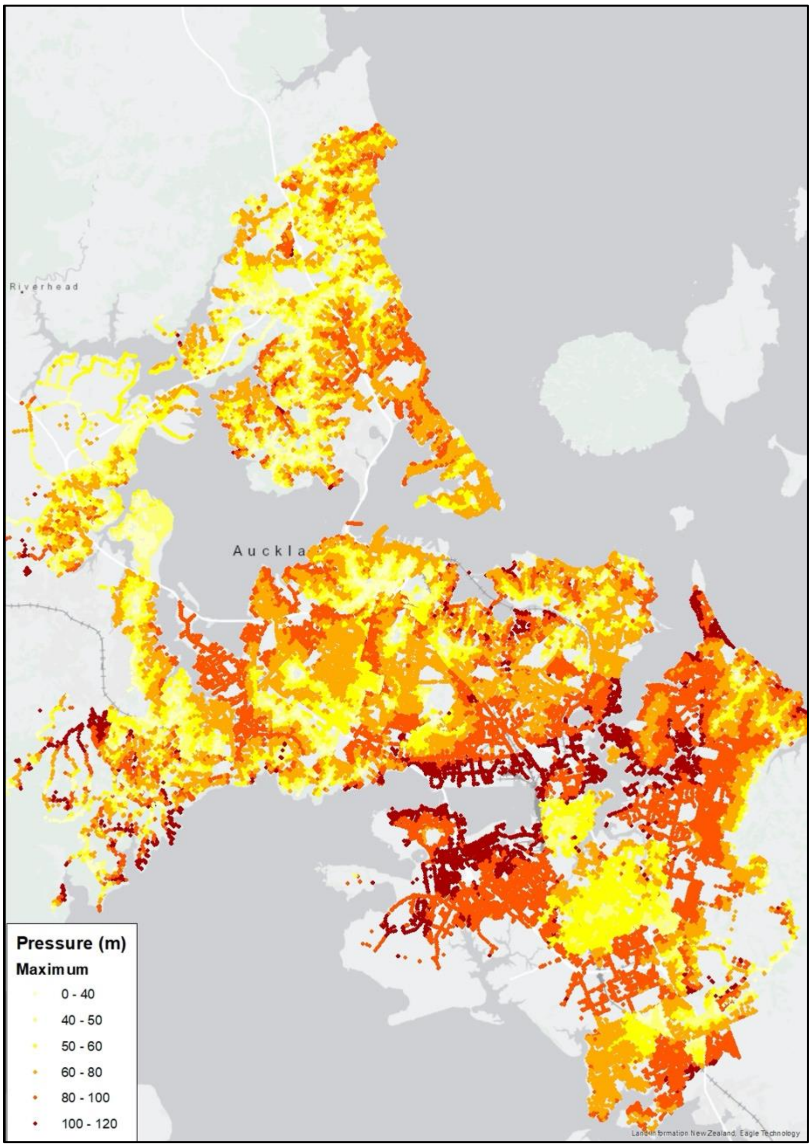

Figure 3: Distribution of maximum modelled pressure in Auckland's water distribution network

2.4 VERTICAL GROUND MOVEMENT GIS

Indicators of vertical ground movement were obtained from the Synthetic Aperture Radar interferometric data of the Sentinel-1 satellites. The raw interferometric data is provided free of charge by the European Space Agency and the derived ground movement data was calculated during a pilot trial by a third-party service contracted directly to Watercare.

The derived ground movement records contain line-of-sight displacement measurements from locations identified as having fixed, reflective surfaces following multiple satellite passes – these are called scatter points. The dataset contains ground movements from April 2015 until the end of June 2020. Each record in the datasets represents an identified scatter point, and the ground movement values are given in columns using the dates of the measurement as attributes. Other attributes include the derived average ground movement velocity and metadata related to each point's reference system (e.g., the measurement angle and the digital elevation model error). Figure 4 illustrates the coverage of the dataset, colour-coded by average velocity. As shown, most of the points have an average velocity lower than 0.5 mm/year.

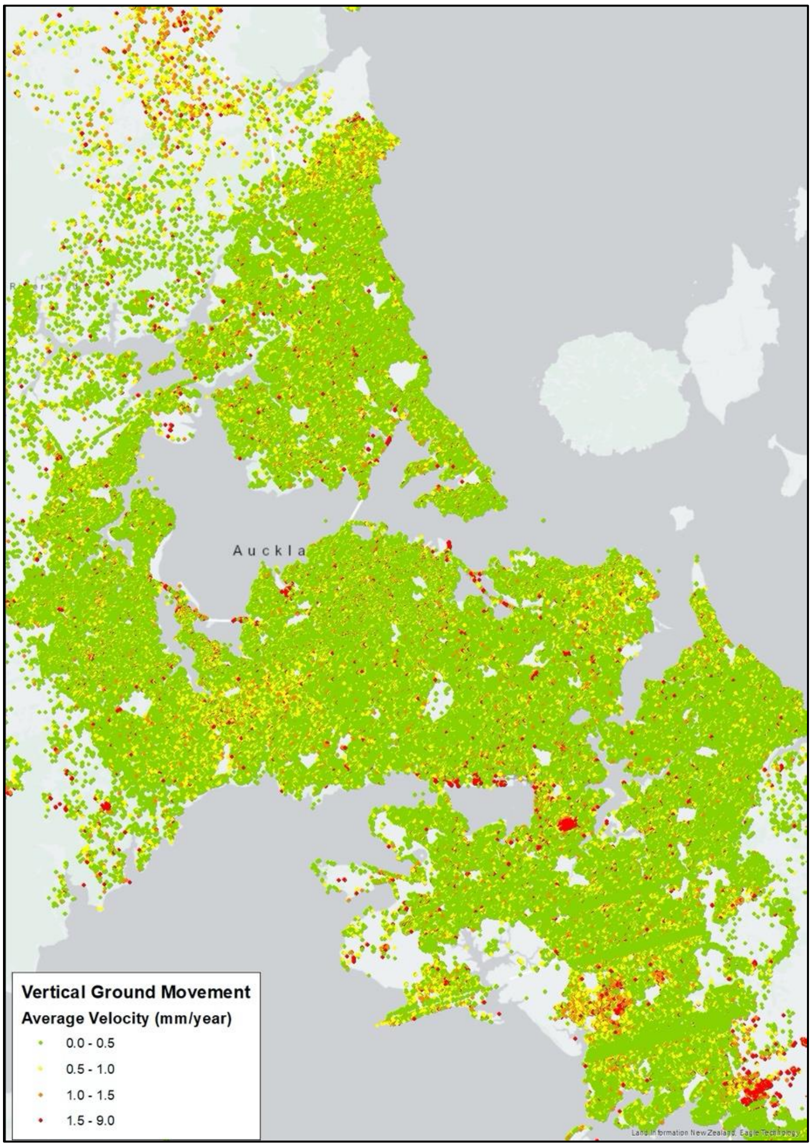

Figure 4: Average vertical ground movement velocity of scatter points in the ground movement dataset.

3 PRESSURE AND PIPE FAILURE RATE

This section describes the investigation into a correlation between the system pressure and pipe failure rate.

3.1 METHODOLOGY

The analysis started by spatially relating the "Pressure nodes" and "Water pipes" datasets and assigning to each pipe the pressure attributes of its nearest point. Specifically, the pressure attributes included are "max pressure", "min pressure", and "pressure fluctuation". Next, the Water pipes dataset was purged to remove service pipes and pipes with invalid diameter, pressure, or material attributes.

The descriptive statistics of the pressure variables in the final dataset are presented in Figure 5. The maximum and minimum pressure variables show a similar range of approximately 5 to 110m (including outliers). Although, the mean maximum pressure is about 10m higher. This difference is also reflected in the complementary variable pressure fluctuation with a mean of approximately the same value. Additionally, the pressure fluctuation of 50% of the pipes is in the range of 3 to 13m, and the maximum difference between pressures is 38m. These modelled distributions suggest surplus pressure exists in the distribution network.

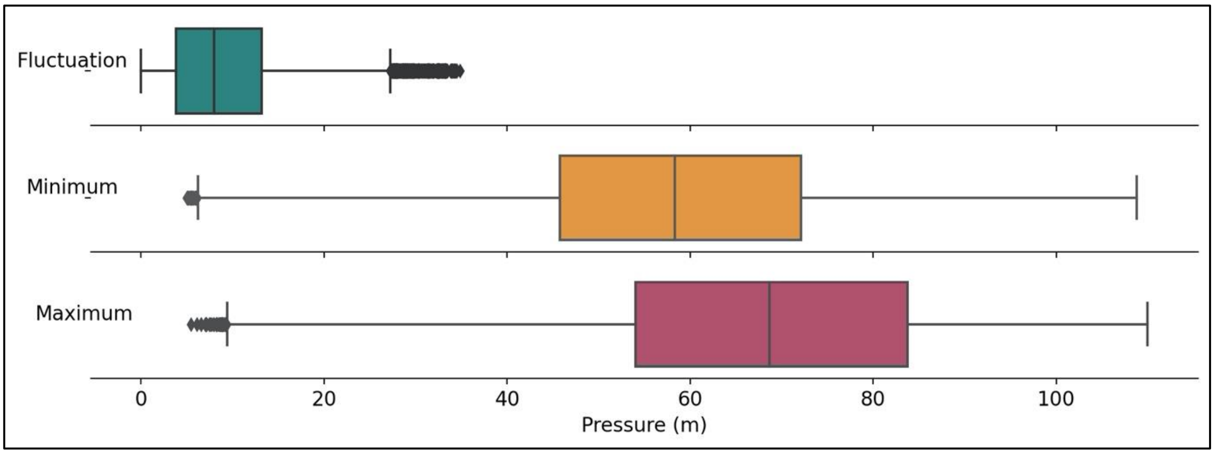

Figure 5: Distribution of system pressure

Once the variables were individually analysed, the dataset was segregated by material, diameter and maximum pressure range. The pressure range only considered the maximum pressure associated with a pipe, since this is considered representative of the maximum pipe wall stress the pipe is likely to be exposed to. Finally, the failure rate of each material-diameter-pressure category was calculated and plotted.

3.2 RESULTS

The results for AC, PE and PVC (material specific) are shown in Figure 6, Figure 7 and Figure 8 respectively. The figures display the following parameters:

- A bar plot showing the pressure range and number of data points in each range for all diameters of that specific material.
- A scatter plot showing average failure frequency in each diameter range against the maximum pressure, as well as a linear regression. Each series in represents a total number of failures and total pipe length in each diameter category (refer legend for each series).
- The title gives the material, total failures over the period and total pipe length represented by the plot.

Figure 6 shows a positive correlation between the failure rate of AC and maximum modelled pressure. An increase in the failure rate was found with a reduction of diameter. This inverse correlation is consistent with data found in other published studies (Kettler & Goulter, 1985; Giustolisi & Berardi, 2009; Christodoulou, 2011). The slopes of the linear regressions for all diameter ranges are remarkably similar at approximately 0.001 failures/km/year/m.

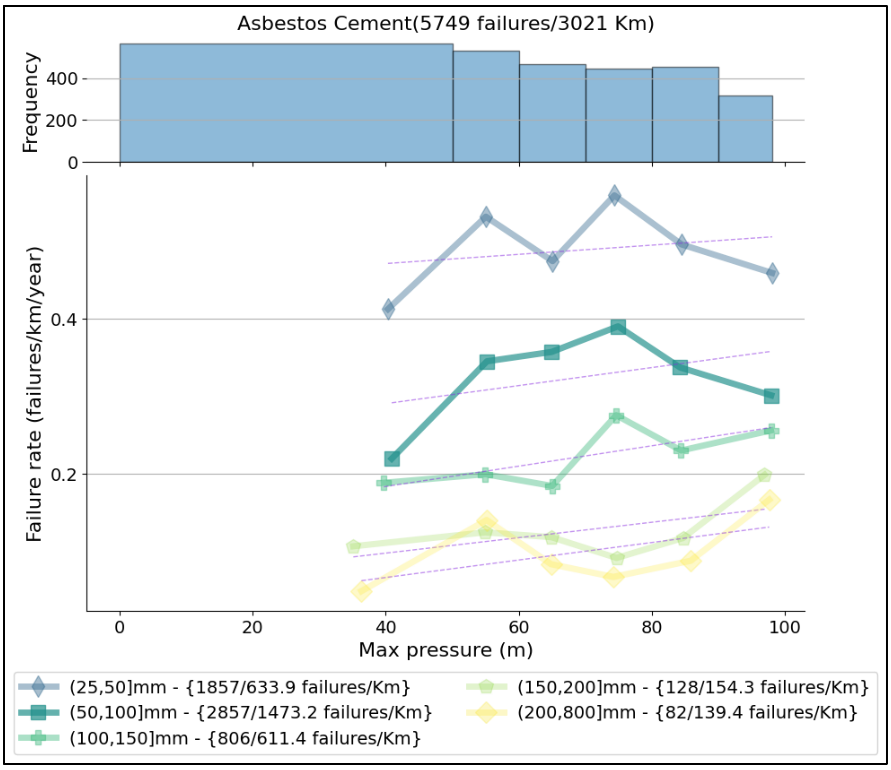

Figure 6: Failure rate against maximum pressure in AC pipes.

Figure 7 shows - for PE - a notable increase in pressure related failure (i.e. increased slope) as the diameter decreases. Nevertheless, all the slopes are positive, so there is also a positive correlation between failure rate and pressure.

Figure 8 shows - for PVC - as in the other two materials, failure rates rise with pressure and marginally reduce with pipe diameter. However, in this case no clear trend was found regarding the various linear regression slopes. Data for the diameter range 200-800mm was removed from Figure 8 due to limited records (i.e., <3% of the materials' total pipe length or number of failure events). This low percentage was expected as outlined in Figure 2.

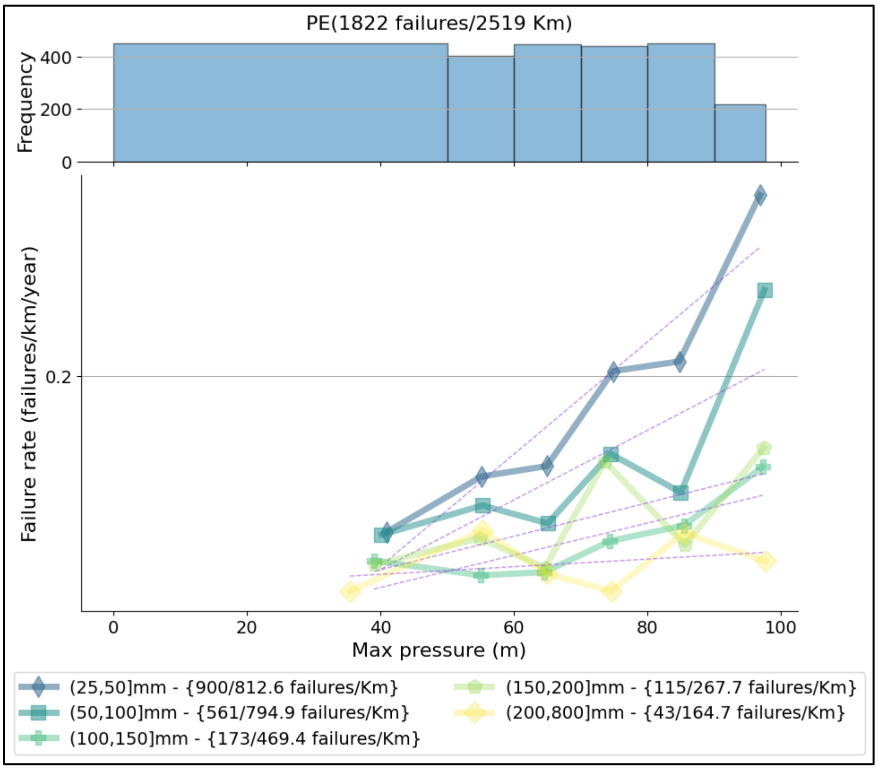

Figure 7: Failure rate against maximum pressure in PE pipes

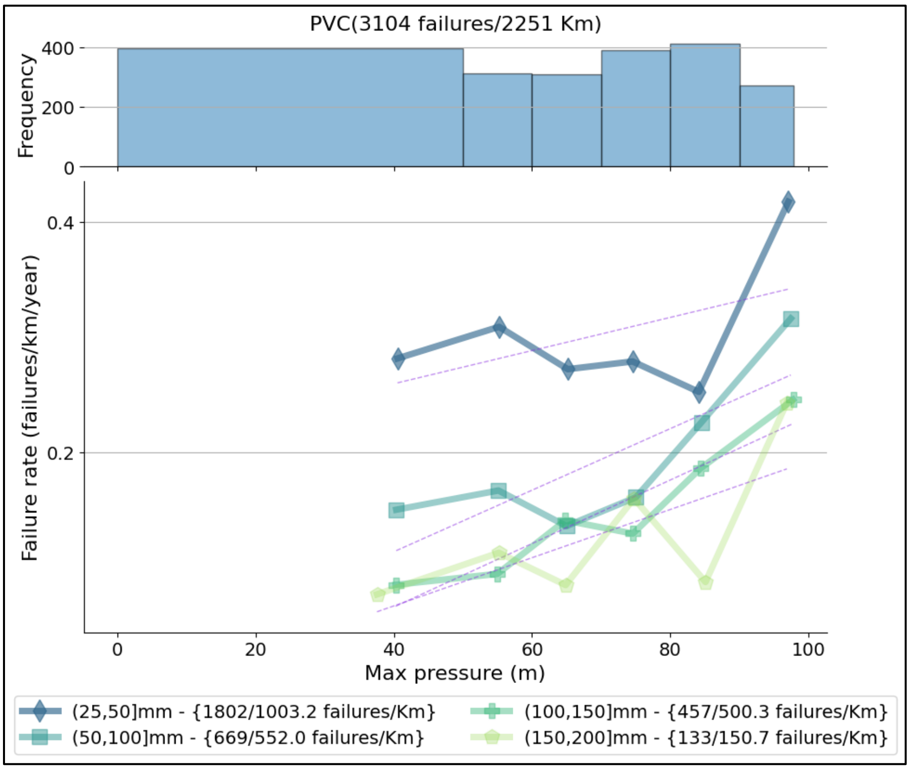

Figure 8: Failure rate against maximum pressure in PVC pipes

4 GROUND MOVEMENT AND PIPE FAILURES

To study the relationship between derived vertical ground movement and pipe failures, the ground movement near failed pipes were evaluated against data from comparable intact pipes during the same time period. This period was named the failure analysis period (FAP) and defined as the 5 months prior, finishing on the date that the specific failure was reported. Four criteria were used as representative values to summarise the ground movement data near the pipes during the FAP. Each criterion represented different ground movement characteristics, producing independent comparisons between the failed and intact pipes.

4.1 EVALUATION CRITERIA

The criteria used in this study focused on the quantity and intensity of ground movements measured along the sightline at locations near the failed pipe. Hence, the criteria evaluated either ground level, movement or velocity of each point associated with a pipe and selected only one point to represent the pipe's stress. In the selected criteria, the pipe's ground movements are represented by the point linked to the pipe with maximum value. Therefore, each of these criteria can then be represented with Equation (*1*):

$$\max_{i \in N_p} f(i) \qquad (1)$$

where N_p is the set of scatter points associated with the pipe and $f(i)$ the specific evaluating function applied to point i. The evaluation functions were defined using the terms X^i, V^{i} and D^i, which represent the set of vertical ground movement measurements, velocities and measurement dates associated to point i respectively. However, since all the scatter points had the same set of measurement dates, D^i could be simplified to D. Explicitly, X^i and D were defined as:

$$\mathrm{X^i} = \{x_1^{\mathrm{i}}, \dots, x_{\mathrm{m}}^{\mathrm{i}}\} \qquad (2)$$

$$\mathrm{D} = \{\mathrm{d_1}, \dots, \mathrm{d_m}\} \qquad (3)$$

$$\mathrm{V^i} = \{\mathrm{v_1^i}, \dots, \mathrm{v_{m-1}^i}\} \qquad (4)$$

where x_j^i is the j ground movement measurement in X_j, D_j the j measurement date in D, v_j^i is the velocity at point i between the j date and the $j+1$ and m the number of measurements within the FAP. Thus, v_j^i was calculated using Equation 5.

$$v_j^i = \frac{|x_{j+1}^i - x_j^i|}{d_{j+1} - d_j} \qquad (5)$$

In this context, the functions used for each criterion are defined below.

4.1.1 MAXIMUM TOTAL

This criterion aimed to determine whether in the months leading up to an historic failure report, the accumulated measured ground movement at point i could be observed as different in failed and intact pipes. It was assumed that the stresses acting on the pipe are the same regardless of the direction of the movement (i.e., compression or expansion). The maximum total criterion is defined as:

$$f(i) = \sum_{j=1}^{m} \left| x_{j+1}^{i} - x_{j}^{i} \right| \qquad (6)$$

4.1.2 MAXIMUM MAX-MIN DIFFERENCE

This criterion calculated the maximum compression or expansion at point i during the FAP, and was defined as:

$$f(i) = max\, X^{i} - min\, X^{i} \qquad (7)$$

4.1.3 MAXIMUM MEAN VELOCITY

This criterion evaluated the stress intensities rather than the movements themselves. Thus, it evaluated the mean ground movement velocity of point i during the FAP ($\bar{V}^{i}$) as follows:

$$f(i) = \bar{V}^{i} = \frac{\sum_{j=1}^{m-1} v_{j}^{i}}{m-1} \qquad (8)$$

4.1.4 MAXIMUM MAX VELOCITY

Similarly, this criterion focussed on detecting specific intense events near failed pipes, and was defined with Equation 9:

$$f(i) = max\, V^{i} \qquad (9)$$

4.2 METHODOLOGY

Initially, the “Water pipes” dataset was separated into failed and intact pipes, using the “number of failures” attribute. Then, the resultant datasets were spatially related to each other and to the scatter points of the ground movement dataset. The pipe-pipe pairs were found using a buffer distance of 400metres from the failed pipe, while the pipe-point pairs were found using a buffer distance of 15 meters from the pipe (See Figure 9).

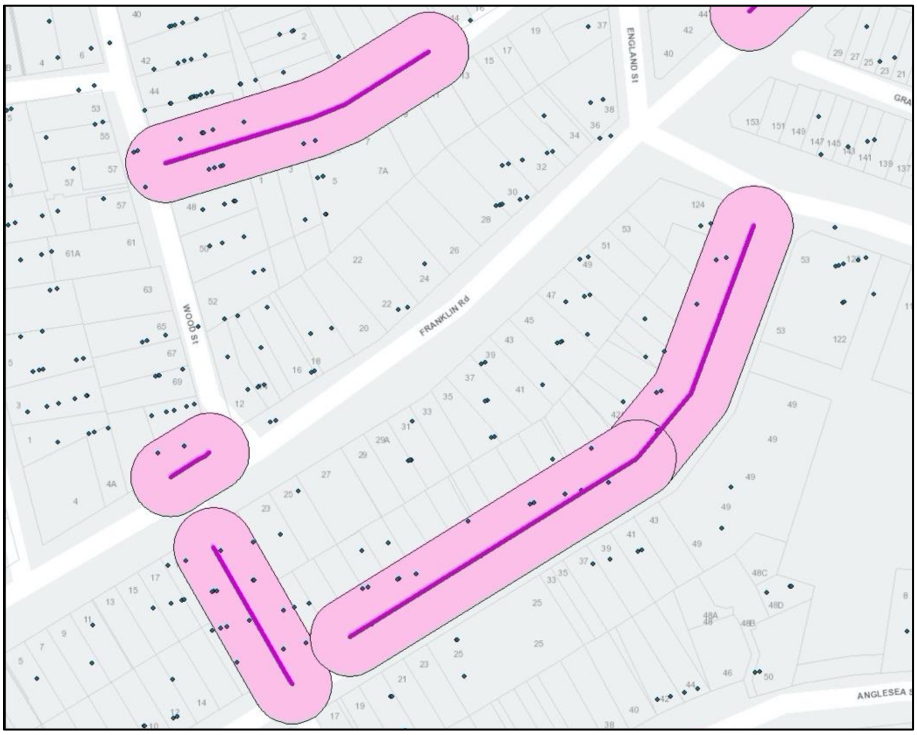

Figure 9: Intersect between the failed pipes dataset and points of the ground movement dataset.

Next, a unique comparison pipe per failed pipe was obtained, by removing inadequate pairs and selecting the pipe-pipe pair with the smallest length difference. Specifically, pairs were marked as inadequate if they have different material, diameter, or a length difference greater than 25% of the failed pipe length. This essentially removed relationships with pipes that were not comparable to the failed pipe. Lastly, the criteria were calculated using Equations 6-9, summarising the ground movement movements for each point, and selecting a representative value for each pipe.

4.3 RESULTS

At the end of this process, the percentage of failures evaluated was 37% of the original failure dataset. From this percentage, 26% of the discarded failures were due to the absence of a suitable comparison pipe and 11% due to the absence of scatter points inside the selected buffer.

The criteria results obtained with the Descending Persistent dataset are summarized in Figure 10. The plots illustrate differences in the shape, range and other summary statistics of each criterion distribution. No significant difference between the failed and intact pipes was evident from the analysis for any of the criteria considered.

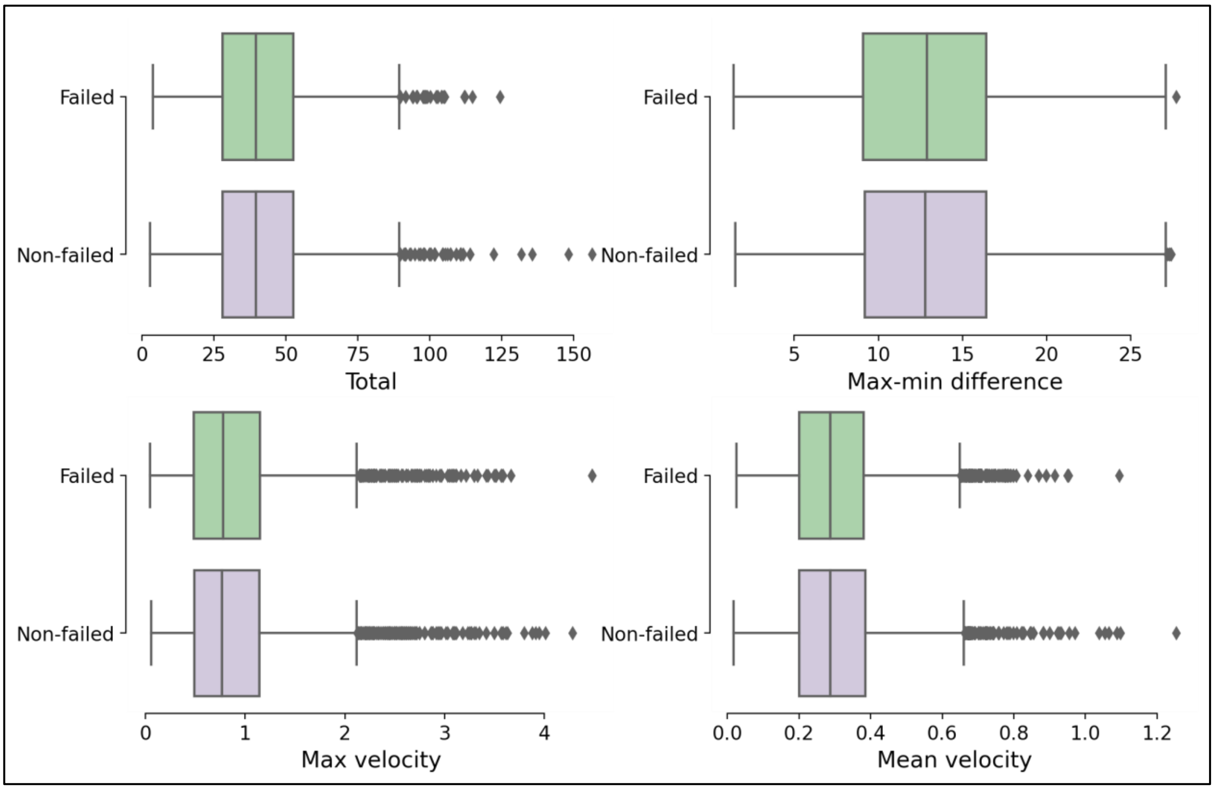

Figure 10: Comparison between failed and intact pipes for all four evaluation criteria

5 CONCLUSION

Despite minor anomalous pipe attribute data which had to be removed, and limitations in the confidence of modelled pressure data, this study identified positive correlations between maximum pressure and failure rates for different pipe diameters and materials. Notably, polyethylene in small diameters was found to have an increased sensitivity to high-pressure exposure. In addition, the inverse relationship between diameter and failure rate was consistent with other referenced studies and supports wider business initiatives which are underway to further reduce pressure in areas of the distribution network.

In relation to data derived from the Sentinel-1 satellites as an indicator of ground movement, no significant difference was observed between ground movement related to failed pipes and intact pipes. However, it is worth noting that data excludes possible unreported or background leaks / failures which themselves could be associated with localised ground movement, among other factors. It is also possible that the ground movement datasets utilised were impacted by a degree of survival bias due to the possible removal of the reflecting surface (i.e. scatter points) near the reported failures as a result of excavation and backfill. Further work is required to associate ground movement indicators with watermain failures.

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