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Analysis of factors driving water main breaks across 13 Canadian utilities

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Abstract

Deterioration of water infrastructure is a global challenge that jeopardizes water system ability to deliver water safely. While various factors affect watermain failure, previous studies have focused on common pipe attributes or general protection strategies. The main objective of this study is to examine the relationship between pipe break characteristics and system properties. Comprehensive data from thirteen Canadian water systems (over 60,000 failures) are examined with correlation and chi-squared analyses. Joint and fitting failures are most likely for pipes aged 20 years or less, and universal joints are most associated with joint failure. Pipes in clay and sand soils are more likely to break due to improper bedding and differential settlement, respectively. Furthermore, in the summer, accidental breaks of asbestos cement pipes are more likely, as are failures of pipes with collar joints and coal tar lined pipes. By exploring these relationships, the paper provides insights into opportunities for reducing water main failure, through improved design, maintenance and rehabilitation.

Keywords Water main failure, Infrastructure deterioration, Data analysis, Important factors, Asset management

Introduction

Watermain breaks can seriously compromise water system service and jeopardize the ability to deliver clean water safely. While the disruption of clean water service might seem like a rare scenario in Canada, 25% of potable water infrastructure is in fair condition or worse (Canadian Infrastructure Report Card 2019). The backlog in upgrading and replacing water and wastewater systems in Canada has been estimated to surpass CAD$ 80 billion (Canadian Infrastructure Report Card 2012).

Across 308 utilities in North America, the rate of main breaks was found to grow from 2012 to 2018 (Folkman 2018). However, a more recent study of five Canadian utilities (Snider and McBean 2020) saw break rates decreased or stabilized in recent years. These trends largely depend on pipe material, install date and rehabilitation practices. For example, Singh et al. (2021) estimated that around 82% of the available cast iron pipes in North America had surpassed their useful life. More specifically, Snider and McBean (2020) observed cast-iron pipes installed post 1941 are deteriorating the fastest among the pipe cohorts analysed.

In addition to material and install date, many other factors in water main design, operation, maintenance and rehabilitation can influence pipe failure rates. Dingus et al. (2002), Rajeev et al. (2015) and Barton et al. (2019) found varying failure rates for different categories of pipes and pipe environments, e.g. diameter, material, age, season. However, a statistical analysis was not performed by these studies. Previous studies seeking to predict water main breaks have also explored the significance of factors, as they contribute to improve the performance of predictive models (Nishiyama and Filion 2014; Robles-Velasco et al. 2019; Aslani et al. 2021; Assad and Bouferguene 2022). These models have largely focused on physical and historical pipe factors which are more readily available, e.g. diameter, length, material and age. Other factors were included depending on case study

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data availability and the objective of the study. The most important factors identified by these studies are also the most common: material, length, diameter, age, and number of previous breaks (Robles-Velasco et al. 2019; Aslani et al. 2021; Assad and Bouferguene 2022).

While previous studies have explored several factors and found correlations to failure rates the impact of specific water system properties, such as lining type and joint type is still not well understood Furthermore, the types of failures (e.g. circumferential, longitudinal etc.) have been largely connected to pipe material and soil type, but other system properties have not been explored. Thus, the primary objective of this study is to examine the relationship between water system properties and break characteristics. Data from 13 utilities across Canada is analysed. By investigating these relationships, this study aims to better understand the factors that contribute to water main failure and inform long-term asset management solutions.

Factors that typically affect pipe failure have been classified under three categories: (1) Pipe Intrinsic: age, diameter, joint systems, lining and coating, defects, damage, chemical degradation; (2) Environmental: weather, soil hazards, hydrogeological conditions; and (3) Operational: network operations, internal pressure, and failures (Barton et al. 2019). While this is a useful framework, it does not describe how factors can be measured, which is key to managing them and improving predictions of water main failure. Because intrinsic pipe characteristics may be related to original characteristics of the pipe itself, historical practices/incidents, or protection activities, these categories of factors are separated herein. Each factor, their most common examples and impact on failure rates is further explored in the following paragraphs.

Pipe material is largely applied in estimating pipe expected service life (Hudson and Haas 2013). Although many other factors exist, the type of break and break rate has been found to significantly differ by material. A survey of 308 North American utilities indicated that circumferential breaks and corrosion were the two most common types of breaks in ductile iron (DI) and cast iron (CI) pipes (Folkman 2018). For polyvinyl chloride (PVC) pipes, scratches, voids, and inclusions are more common (USEPA 2012). An analysis of asbestos cement (AC) pipes found more than 90% of failed pipes had a circumferential break (Hu and Hubble 2007). Circumferential breaks are more prominent in less flexible metallic pipes, as they are caused by longitudinal stress, soil movement or improper bedding (O'day et al. 1986). Among CI, DI, steel, and AC pipes, lower break rates have been observed for DI (Rajeev et al. 2015). This was confirmed in a comparison of CI and DI pipes, as well (Snider and McBean 2020). The deterioration of the pipe materials can be delayed with protection activities, such as lining, coating and cathodic protection. For example, lining was found to increase expected service life by 30–50 years (USEPA 2002). Pipe rehabilitation in general avoided 50 to 67% of breaks for two case study systems in Ontario (Snider and McBean 2022). However, the impact of the type of lining or coating on failures was not investigated.

Pipe diameters have also been observed to affect the rate and cause of failure. Kettler and Goulter (1985) found a very strong inverse correlation (− 0.96) between failure rate and pipe diameter for Winnipeg pipes between 100 and 300 mm. Large diameter pipes generally experience fewer breaks, most of which are holes and longitudinal breaks (Rajeev et al. 2015). Holes are caused by corrosion and longitudinal breaks by excessive pipe pressure or external loadings, such as traffic and frost (O'day et al. 1986). Smaller diameter pipes (< 200 mm), more frequently installed in water distribution systems (Hu and Hubble, 2005; Folkman 2018) have higher failure rates (Barton et al. 2019) and experience more circumferential breaks. Pipes are generally classified in three service types: i.e. transmission, distribution or service. Transmission pipes convey water from the source and are usually large diameter, whereas service pipes convey water to the end use and are smaller. Distribution pipes carry water from transmission and distribute it throughout the system. Pipes of each type are not only sized differently, but also operated and maintained differently since the consequence of a transmission main failing is significantly higher (Kleiner 2001).

Pipe length is also identified as an important factor by many authors. However, there isn't a consensus about whether breakage is positively (Berardi et al. 2008) or negatively (Wang et al. 2009; Nishiyama and Filion 2014) correlated with breaks. On the other hand, greater pipe depth and thickness have been consistently found to reduce rate of failure (Rajani et al. 1996; Asnaashari et al. 2009). Looking beyond the pipe, joint failure is typical albeit less studied. Joint failure was found to cause 15 and 16% of all PVC pipe failures by Dingus et al. (2002) and Burn et al. (2005), respectively. Rigid joints are more sensitive to rotation than flexible joints and are more prone to leak and fracture failure due to ground movement (Barton et al. 2019). However, types of rigid or flexible joints more likely to fail were not contemplated.

Age has been found to be one of the most important factors affecting failure (Berardi et al. 2008). However, age alone is not a reliable predictor of watermain failure (Kahn et al. 2020). Age is a proxy for other environmental and operating factors that accumulate over time to deteriorate the pipe. Furthermore, pipes that have already broken are more likely to break again, as the factors that contributed to the first breaks accumulate and cause further breaks (Walski and Pelliccia 1982; Raed et al. 2010;

Scholten et al. 2014). An early study of Winnipeg found 22% of failures occurred within 1m of another failure and 46% within 20m, with 42% of these failures happening within one day of the initial failure (Goulter and Kazemi 1988).

Higher operating pressures in water distribution networks have been widely shown to increase probability of failure (Barton et al. 2019). Sudden changes in internal pressure, caused by marked fluctuations in consumption or operational events such as testing fire hydrants or pumping station failure, can also add stress to pipes and increase risk of failure (Martínez-Codina et al. 2016). Pressure-related failures are more common in large diameter pipes since smaller diameters are generally used in lower pressure areas and experience a lower rate of transient surge pressure (Rajeev et al. 2015; Ruchti 2017).

Soil properties can influence pipe failure indirectly, i.e., corrosion or directly, i.e., soil movement. Corrosivity depends on many characteristics, including resistivity, redox potential, sulfide content, and moisture (AWWA 2009). Soils with greater swelling capacity lead to greater movement and higher failure rates (Singh et al 2021). However, the swell capacity is difficult to determine. Under freezing temperatures, ground swelling and multiple freeze and thaw cycles increase external loads and thereby pipe failure (Bruaset and Sægrov 2018). While Bruaset and Sægrov (2018) did not find an increase in break rates at higher temperatures, Wols and Van Thienen (2014) observed that greater water consumption and lower groundwater levels during hot dry summers impose additional internal and external loads, also causing more breaks. Both studies used linear regressions to quantify the correlation between weather and failure rates. Bruaset and Sægrov (2018) predicted failure rates for all materials of Norwegian systems (25,573 failures) based on the average temperature the preceding week, with a R^2 of 0.813. Wols and Van Thienen (2014) developed separate models for different materials of Dutch systems (10,325 failures) and found correlations only for certain materials, i.e., asbestos cement (R^2 0.54), steel (R^2 0.71) and cast iron (R^2 0.56). Other factors that might influence the impact of weather, such as soil type, were not considered.

Methodology

The methodology of the present study comprises four steps: data understanding, data cleaning, data preparation, and data analysis. Each of these steps is explained in more detail in the following paragraphs.

Data understanding

Each of the utilities were asked to provide two datasets, a pipe inventory, and a break history, either in Excel or GIS format. The first step in data understanding was creating metadata tables. These tables described all attributes collected by each city, including a unique name, type as well as range and unit for numerical attributes or categories for categorical variables. This enabled researchers to better understand the data, identify issues and select relevant attributes. Any inconsistencies or issues in the data were flagged and discussed with the utilities so they could be adequately addressed.

Data cleaning

Data cleaning comprised the definition of unique categories, missing value imputation and outlier removal. Because each utility employed different categories for the same attribute, a set of unique categories was defined. For example, all material names were standardised. In the case of failure type and cause attributes, certain utilities defined categories while others collected information in short text fields that were filled out by operators as free form text. Based on the available categories and text, a unique set of categories was defined for failure cause and type. Eight categories of failure cause were defined as follows: accident, corrosion, deterioration, differential settlement, fatigue, improper bedding, stress and temperature change. Ten categories of failure type comprised: blowout, break, circumferential, crack, hole, joint and fitting, leak, longitudinal, not on main, and other.

Data cleaning templates were developed for each utility to map their data to the unique categories in PowerBI. Consistent units were also defined for all numerical attributes. Missing data was filled through different approaches, depending on the type of attribute. Pipe material, diameter and depth were assumed to be the same of adjacent pipes, if data was available in GIS. If spatial data was not available, material was based on the most common material of that install year. Diameter and depth were assumed to be the mode. Protection status was taken to be "Yes" if protection materials and/or age was provided. If no information on protection was provided, the pipe was assumed not to be protected, as this is the most common case. Install year was based on the mode year for pipes of the same material. Pipes with incorrect values, such as zero diameters or length, or negative ages, were removed from the analysis.

Data preparation

In discussion with the participating utilities, two key quantitative indicators of water main failure were selected, break status and current rate of failure. Break status was established as a binary variable, either 0 if the pipe didn't break during a given year, or 1 if it did break. Current rate of failure was calculated as number of breaks per length (in km) per year. While the first requires records of both broken and non-broken pipes, the second accounts only for broken pipes. To analyse the correlation of categorical and numerical attributes, categorical variables were converted to numerical through optimal scaling. The optiscale library of the Gifi package in R was applied to determine unique scores for each category of each factor.

Data analysis

To reveal the strength of relationships between different variables and the targets, correlation analyses were conducted. Correlations were determined for all data and by utility. Results by utility were summarized in a box plot. In the correlation analyses, a correlation coefficient greater than 0.8 was considered very strong, 0.6 to 0.79 strong, 0.4 to 0.59, moderate and 0.2 to 0.39 weak, as applied by Jun et al. (2020).

To further explore the impact of specific categories of factors on failure, chi-squared analyses were conducted (Jafar and Juran 2007). The chi-square test is a robust solution for testing hypotheses about nominal categorical variables. Furthermore, it can be used for data that is not equally distributed across categories, a condition that can render conventional tests like t-tests and ANOVA unreliable (McHugh 2013). A p-value equal to or smaller than the null hypothesis ($p=0.05$), rejects the null hypothesis, indicating an association. Pearson residuals were plotted in heatmaps. These analyses and visualizations were coded in Python.

Description of case study systems

Data was collected from thirteen utilities across Canada, in the provinces of Alberta, British Columbia, Manitoba, Nova Scotia, Newfoundland and Labrador, Ontario and Saskatchewan. Each utility provided an inventory and history of main breaks, totalling 25,906 km of pipes and 62,023 break records. The attributes collected by each utility are summarized in Table 1. Diameter, material, length, installation year, and failure year were consistently collected by all utilities. Because these physical and historical attributes can be easily recorded at the time of installation or break, their availability is expected. Other less collected factors include joint type, roughness, pipe depth, whether the pipe is restrained, and whether the pipe is a dead end. The following sections summarize the key characteristics of the dataset and point to potentially important factors.

As pipe materials and manufacturing processes have evolved, the percentage of each material has changed over the years, as shown in Fig. 1. The pipe installation pattern indicates that before 1960, cast iron was the predominant material in the systems. However, this pattern shifted in the 70s as ductile iron became more prominent. Soon after, in the 80s, PVC became more common. Accordingly, cast iron pipes are generally the oldest in

Table 1 Available attributes in each utility

	Physical								Historical						Protection							Operational		Environmental
Utility	Length	Material	Diameter	Joint type	Pipe depth	Restrained	Dead end	Roughness	Install year	Failure year	Failure Month	Status	Failure Type	Failure Cause	Cathodic Protection status	Cathodic Protection year	Lining status	Lining year	Lining material	Coating material	Casing material	Service type	Pressure	Soil type
A	■	■	■		■	■			■	■	■	■	■	■	■						■	■		■
B	■	■	■				■		■	■		■	■	■										
C	■	■	■						■	■	■	■	■		■	■	■	■	■					
D	■	■	■						■	■	■		■	■			■	■	■					
E	■	■	■						■	■	■	■	■	■	■		■	■	■					
F	■	■	■		■			■	■	■	■				■	■	■	■						
G	■	■	■					■	■	■	■	■	■	■			■	■	■					■
H	■	■	■	■					■	■			■	■				■	■					
I	■	■	■					■	■	■	■		■	■										
J	■	■	■		■				■	■	■		■	■	■				■	■		■		
K	■	■	■					■	■	■	■		■	■			■		■				■	
L	■	■	■						■	■	■	■					■	■	■			■		
M	■	■	■	■					■	■	■	■	■	■	■					■				

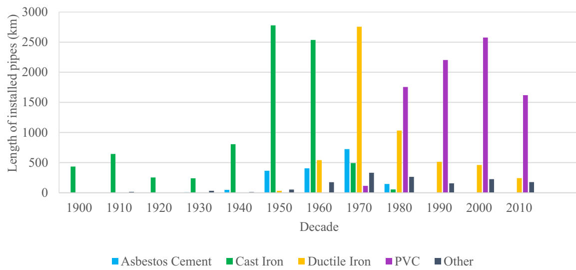

Fig. 1 Total length of material installed each decade for all 13 case study utilities

these systems, whereas PVC are the youngest. The average age of cast iron, ductile iron and PVC pipes are 60 years, 35 years, and 18 years, respectively.

While PVC is the most present material today, the majority of historical breaks recorded by the utilities occurred on older cast iron pipes (Fig. 2). The next most common broken pipe materials are ductile iron, asbestos cement and PVC. Other, less installed materials include concrete, copper, brass, and high density polyethylene (HDPE). Historical breaks, however, were not collected for the same period for all utilities, nor were data collection practices consistent. Table 2 shows the decades of historical break data collected by each utility. While utilities B, H and M began collecting data in the 50s, J and L only have records from the last two decades. Thus, the percentage of breaks by materials is not representative of all utilities for all decades. Figure 2b shows the sample of broken pipe materials for recorded breaks. To address

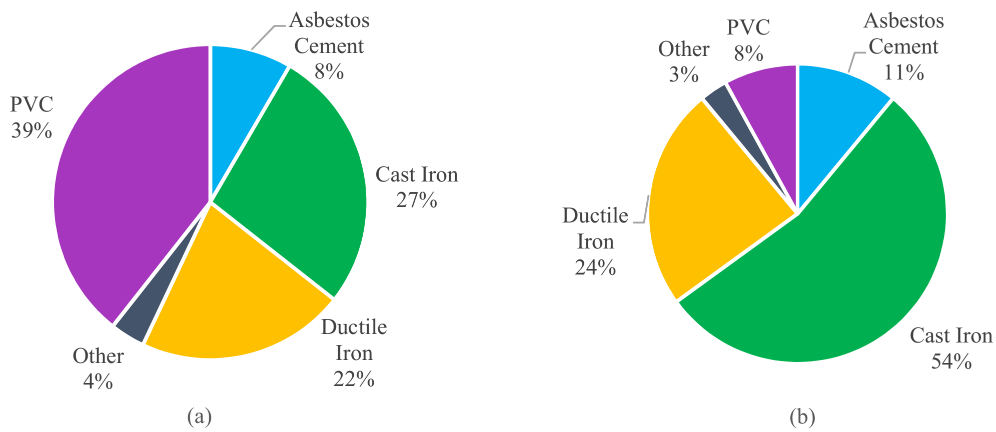

Fig. 2 Percentage of material by total length in **a** inventory and **b** break records for all 13 case study utilities

Table 2 Decades of breaks available, as well as length and number of pipes and breaks in inventory and break datasets

Utility	Length (Inventory) km	Length (Break) km	Break Decades Available 50	60	70	80	90	00	10	Number of pipes	Number of Breaks
A	897	61								7,003	922
B	6,811	1,048								62,090	15,851
C	3,183	440								24,584	5,857
D	2,710	384								18,289	5,733
E	1,084	145								15,511	1,912
F	1,501	147								11,366	2,301
G	392	18								4,565	184
H	1,363	238								35,506	6,515
I	694	96								9,424	1,478
J	1,577	29								66,846	740
K	351	74								3,264	686
L	481	53								7,782	709
M	4,862	576								11,8619	19,135

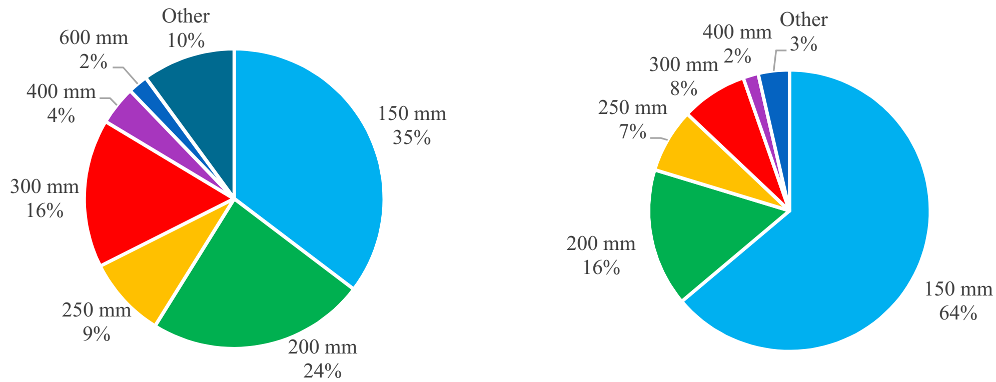

Fig. 3 Percentage of pipe diameters by total length in **a** inventory and **b** break records for all 13 case study utilities

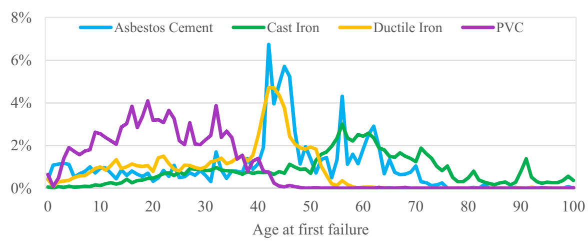

Fig. 4 Frequency of age at first failure by material for all 13 case study utilities

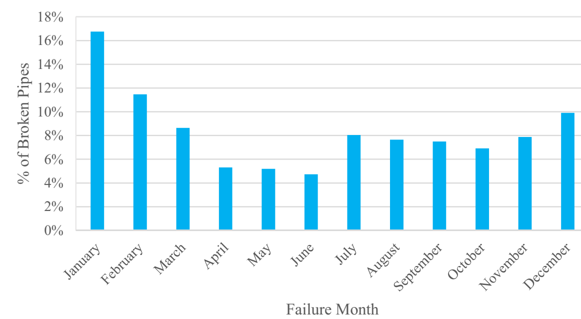

Fig. 5 Failure month (Data for n = 11 utilities, excluding utilities B and H which did not collect this information, as indicated in Table 2)

these inherent shortcomings in data collection, the subsequent correlation analyses consider utilities separately and present the range of results.

The comparison of pipe diameters in the inventory and break datasets reveals that breaks are more frequent in smaller pipes (Fig. 3), confirming findings from previous studies (Barton et al 2019). While 150 mm pipe diameters represent 35% of all pipes, they are 64% of breaks.

Because most of the PVC pipes were installed in the 80s or more recently, they have not yet reached their expected service lives. The frequency plot of age at first failure by material, highlights that PVC breaks recorded so far are early failures (Fig. 4). The mean time to first failure (MTTFF) for PVC pipes is 24 years, ductile iron 43 years, asbestos cement 45 years, and cast iron 61 years. It is expected that these early PVC breaks would not be related to deterioration, but to accidents, manufacturing errors or installation issues. Longer records of installed PVC are required to understand the factors that lead to later failure. Because of this limitation, specific conclusions related to PVC pipe deterioration are not reached in the current study.

Break frequency by month elucidates the impact of weather on main breaks (Fig. 5). More failures are experienced in January and February, during freezing winters. This confirms the findings of Bruaset and Sægrov (2018) who highlighted that freezing temperatures and multiple freeze and thaw cycles lead to more pipe failure. A spike in breaks is also observed in July with hot and dry summers. This pattern matches the accounts of Wols and Van Thienen (2014) who observed that greater water consumption and lower groundwater levels during hot dry summer led to more breaks. Overall, these results show monthly differences can be significant and can be better planned for in maintenance and repairs.

The most common type of pipe protection in the networks is lining. While seven utilities collect information on lining status, only three have data on cathodic protection, and two on coating or casing. Among the utilities with lining information, 20% of pipes are lined. In general, the average lining age at the time of break is 14 years, whereas the overall average lining age is 18 years. Therefore, most lined pipes last more than 14 years after lining.

Operational factors collected by the utilities include service type and pressure. Service type comprises three classes: transmission, distribution and service. Most pipes in the dataset, 90%, are distribution. Fewer, 9.5%, are transmission mains and the remainder are service pipes. Pressure is only collected by one utility, K, and is provided as an average by zone.

Among environmental factors, only soil type is collected by two utilities: A and G. The types of soil include clay, sand, gravel, silt, granular, marsh, muck, and rock. Each area of the systems can be classified as one single soil type or a mix. The most common soil type in utilities A and G is clay, as show in Fig. 6.

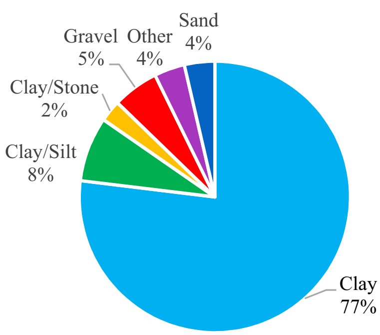

Fig. 6 Percentage of available soil type (Utilities A and G)

Results

Correlation analysis

To evaluate the relationship between attributes and main breaks, several correlation analyses were conducted. First, all common attributes, i.e., material, diameter, length and age were correlated to the two target attributes, current rate of failure and break status. Previous rate of failure was also added to the current rate of failure analysis and is shown to have the highest correlation (Fig. 7). This is aligned with findings of previous studies that note that once a pipe breaks it tends to break more frequently (Walski and Pelliccia 1982). Results of the break status analysis show material and length are the most correlated to the target. However, none of the common factors show a strong correlation to either target.

The correlations between attributes and targets differ by utility. The box plot in Fig. 8 summarizes the correlations to current rate of failure for all utilities. As expected, length is the most correlated attribute to rate of failure (median correlation of 0.97) as the latter is calculated as number of breaks per length per year. Previous rate of failure has a moderate correlation to rate of failure (up to 0.42), and age (up to 0.38), a weak correlation, depending on the utility. All other attributes have insignificant correlations.

Correlations between pipe attributes and break status, Fig. 9, show material may have a strong correlation (up to 0.65). Length (up to 0.53), cathodic protection status (0.53) and cathodic protection age (0.53) are moderately correlated to break status. Joint type (up to 0.33), age (0.29), failure month (0.37), lining status (0.25), lining material (0.25), and roughness (0.33) may have a weak correlation. The variation of correlation coefficients for material (0.07 to 0.65) and cathodic protection status (0.08 to 0.53) is wide. This may suggest that certain materials may not influence deterioration as significantly as others, or that other factors such as pipe protection lead to different behaviours of the same material.

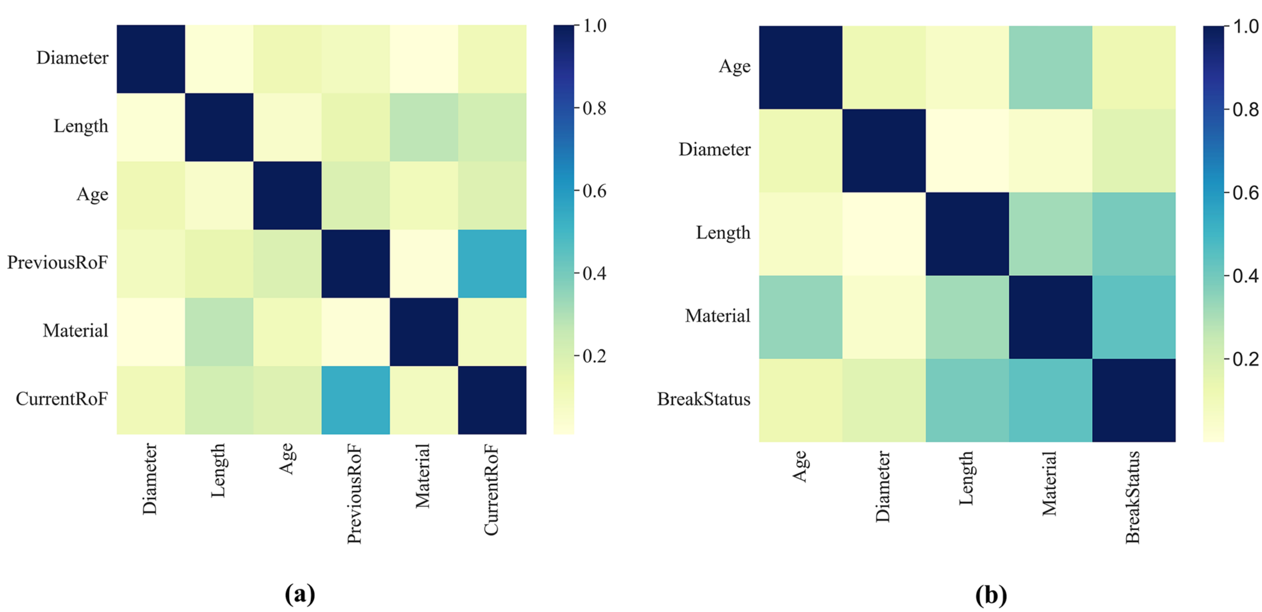

Fig. 7 Correlation analysis between common attributes and **a** current rate of failure, and **b** break status for combined data (n = 13). Correlation > 0.8 very strong, 0.6–0.79 strong, 0.4–0.59 moderate and 0.2 to 0.39 weak

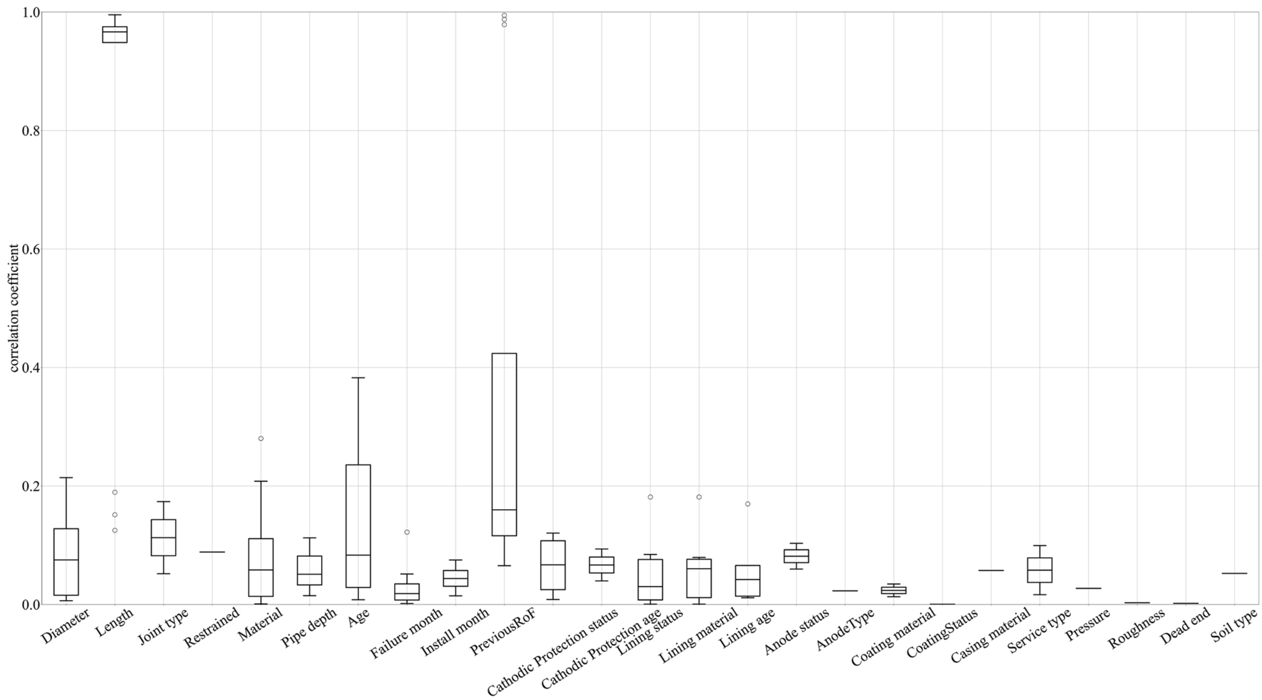

Fig. 8 Correlation analysis between all attributes and rate of failure for all utilities (n = 13) (Correlation > 0.8 very strong, 0.6–0.79 strong, 0.4–0.59 moderate and 0.2 to 0.39 weak)

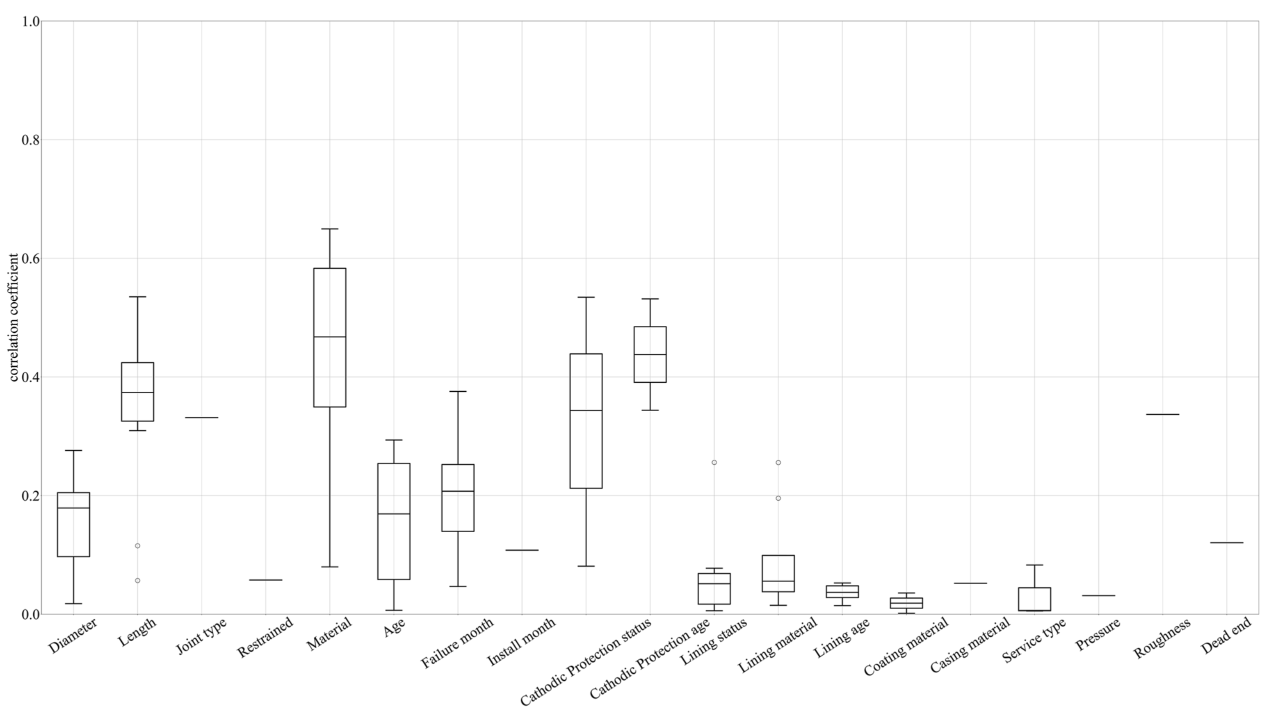

Fig. 9 Correlation analysis between all attributes and break status for all utilities (n = 13) Note: Correlation > 0.8 very strong, 0.6–0.79 strong, 0.4–0.59 moderate and 0.2 to 0.39 weak

Furthermore, results show the protection status itself is generally less correlated with breaks than the age of the protection.

Chi-squared analysis

While the correlation analyses provide some insight into the relation between attributes and failure, they do not show which characteristics are prone to breaks. To further evaluate the relation between specific classes of attributes and failure characteristics, chi-squared analyses were conducted. The analyses considered variables with multiple classes, i.e., material, diameter, soil type, joint type, lining material, and age, and their relation to failure type, cause and month. Due to low data availability the following attributes were not included in the chi-squared analysis: restrained status, install month, coating material, casing material, cathodic protection age, pressure, roughness, and dead-end. Lining status and cathodic protection status were also not included because these attributes only have two classes, protected or non-protected, and the protected status is known to reduce corrosion failures. Thus, further insights can be gathered by analysing different protection types and materials, instead. Results are provided in Table 3. Material, diameter, age and lining material are associated with all failure characteristics. Soil type is related to failure type and failure cause. Joint type, on the other hand, is associated with failure type and failure month. There wasn't enough common data to establish an association between joint type and failure cause.

The values indicate whether there is an association between the attributes. However, it does not reveal how strong the relationship is or how different classes of variables are associated. To do so, the Pearson residuals resulting from the chi-squared analysis were plotted onto heatmaps. Negative values in the heatmap indicate negative associations, while positive values indicate positive association. The absolute values indicate how strong the relation is.

The heatmaps for materials (Fig. 10) show accidents are more likely for asbestos cement pipes. Asbestos cement pipes are also more likely to break in July, August and September. Given that these months align with the construction season in Canada, it is expected that accidents are higher this time of year. To avoid these accidents, better asbestos cement pipe location information would be valuable, as would educating contractors. For cast iron pipes, differential settlement is more likely to lead to failure, specifically of the circumferential type. On the other hand, corrosion and holes are more likely for ductile iron pipes. The results for ductile iron and cast iron pipes confirm typical failure characteristics reported in the literature (Folkman 2018; Hu and Hubble 2007; O'day et al. 1986; Snider and McBean 2022; Barton et al. 2019).

Diameters were categorized into small (≤200 mm), medium (>200mm and ≤400mm), and large (>400 mm) so that similar chi-squared analyses could be performed. The heatmaps in Fig. 11 shows accidents are more common for medium to large diameter pipes, as are joint and fitting failures. Furthermore, for medium pipes more failures occur between May and October, which is like the summer trend of accidents observed for asbestos cement pipes. On the other hand, small pipes are more likely to break in the winter, between December and March. These small pipes also experience more circumferential breaks, confirming observations by Bruaset and Sægrov (2018).

Pipe ages were classified into 20-year buckets. Unsurprisingly, accidents are more likely for pipes aged 20 years or less, likely due to manufacturing or installation errors. For pipes in the same age category, joint and fitting failures are more likely. This may indicate that most installation errors occur at the joints and fittings. Differential settlement becomes more likely in the second phase, between 20 and 40 years. Later, between 40–60 years, circumferential breaks are more likely, and above 60 years, longitudinal breaks (Fig. 12).

The associations between soil types and failure cause and type are provided in Fig. 13. Circumferential breaks are more likely in clay soils. Circumferential breaks are often caused by soil movement that increase longitudinal stress. This is confirmed by the association between clay soil breaks and improper bedding or temperature changes. Pipes in sandy soils are more likely to undergo differential settlement and accidents. Furthermore, different from other soils, failure is more likely on the joint or fitting for sandy soils. Gravel and rock are coarser soils and experience less movement. Breaks and holes are more likely in these soils.

Fewer strong associations are observed between joint type and failure type in Fig. 14. The most likely type of joint to fail is the universal. Furthermore, the use of collar joints is associated with more circumferential failures. Collar joints are rigid and limit pipe movement, increasing longitudinal stress. Pipes with collar joints are also

Table 3 Chi-Square analysis P-values ($p < 0.05$ significant)

Attributes	Failure type	Failure cause	Failure Month
Material	0.00	0.00	0.00
Diameter	0.00	0.00	0.00
Soil type	5.67e−12	2.29e−08	0.5
Joint type	0.00	–	3.56e−99
Lining Material	1.4e−56	6. e−25	2. e−13
Age	0.00	1.96e-188	9.95e−170

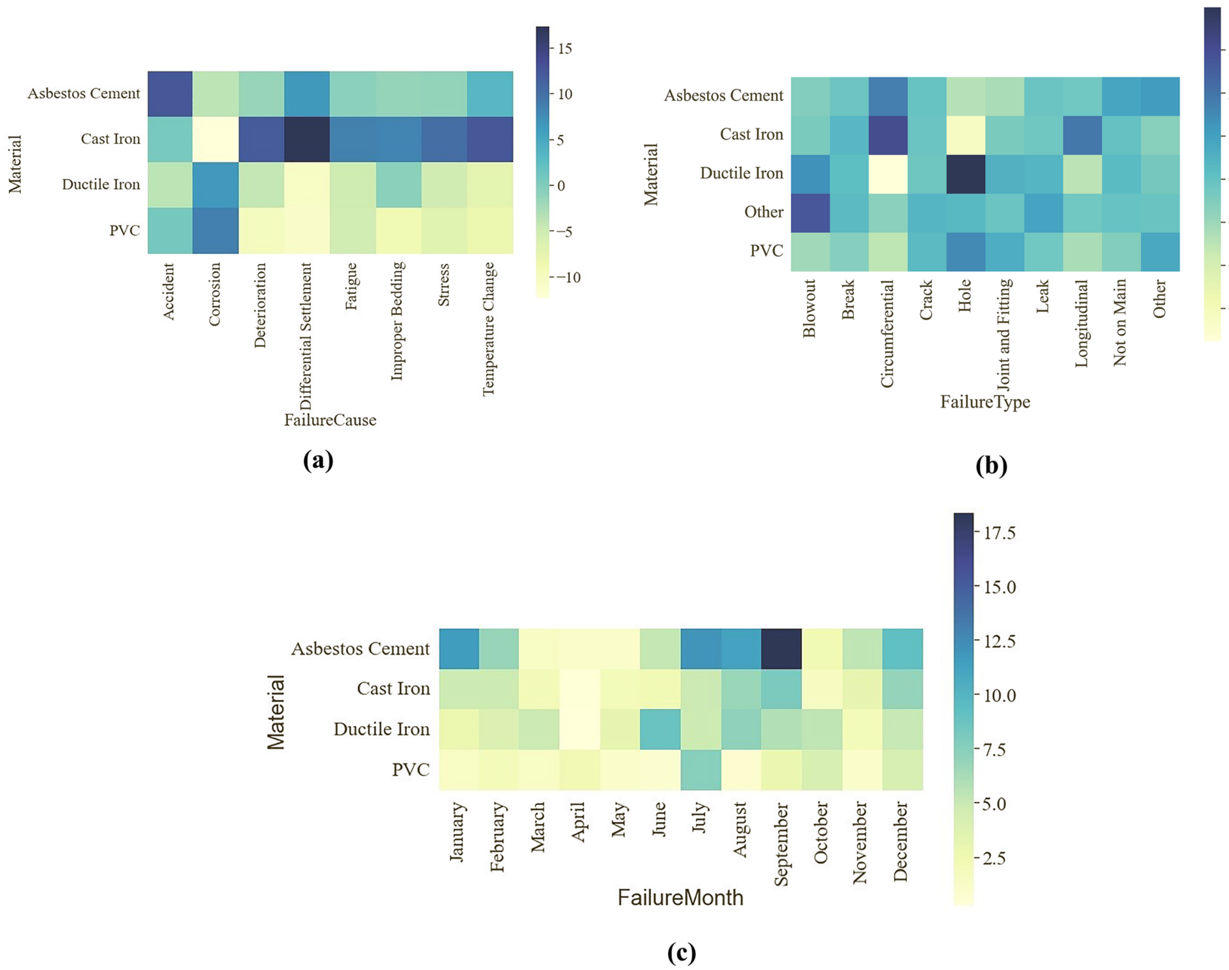

Fig. 10 Association between material and **a** failure cause (n = 10), **b** failure type (n = 11), and **c** failure month (n = 11)

more likely to fail in July, August, September or October. Thus, soil movement due to changes in moisture may lead to failure. However, these results are based only on one utility, and should be further investigated.

In the analysis of lining material, associations between lining type and pipe material are also evaluated because lining practices vary by pipe material. Asbestos cement and PVC pipes are more commonly unlined. Cast iron pipes are more frequently lined with cured in place lining (CIP) or cement lining (CM). CIP and CM lined pipes are also more likely to experience holes, which is related to the corrosion of the original cast iron pipes. Interestingly, corrosion was found to be less likely for cast iron pipes overall, as shown in Fig. 15. The increased likelihood of corrosion in lined pipes may be explained by the fact that pipes that are corroding are more likely to be selected for lining. However, the lining might have been installed too late, or external corrosion is to blame. Indeed, both CIP and CM lined pipes are more likely to fail at the end of summer or early fall. Thus, increased rainfall at the end of summer, and higher soil moisture might contribute to external corrosion. On the other hand. coal tar lined pipes are more likely to experience cracks and in general failures occur in warmer temperatures, i.e., in July. These findings combined indicate coal tar lining is prone to cracking in the heat.

Discussion and recommendations

Initial correlation results confirm findings from previous studies with regards to the importance of material, length, age, previous breaks (Robles-Velasco et al. 2019; Aslani et al. 2021; Assad and Bouferguene 2022), failure month, i.e., weather, (Bruaset and Sægrov 2018; Wols and Van Thienen 2014), joint type (Barton et al. 2019), and pipe protection (Snider and McBean 2022). However, previous studies report results for a group of utilities. Herein the box plots of Figs. 8 and 9 show significant variability in correlations by utility, highlighting the importance of understanding the range of pipe and system properties of each utility and their impact on failure.

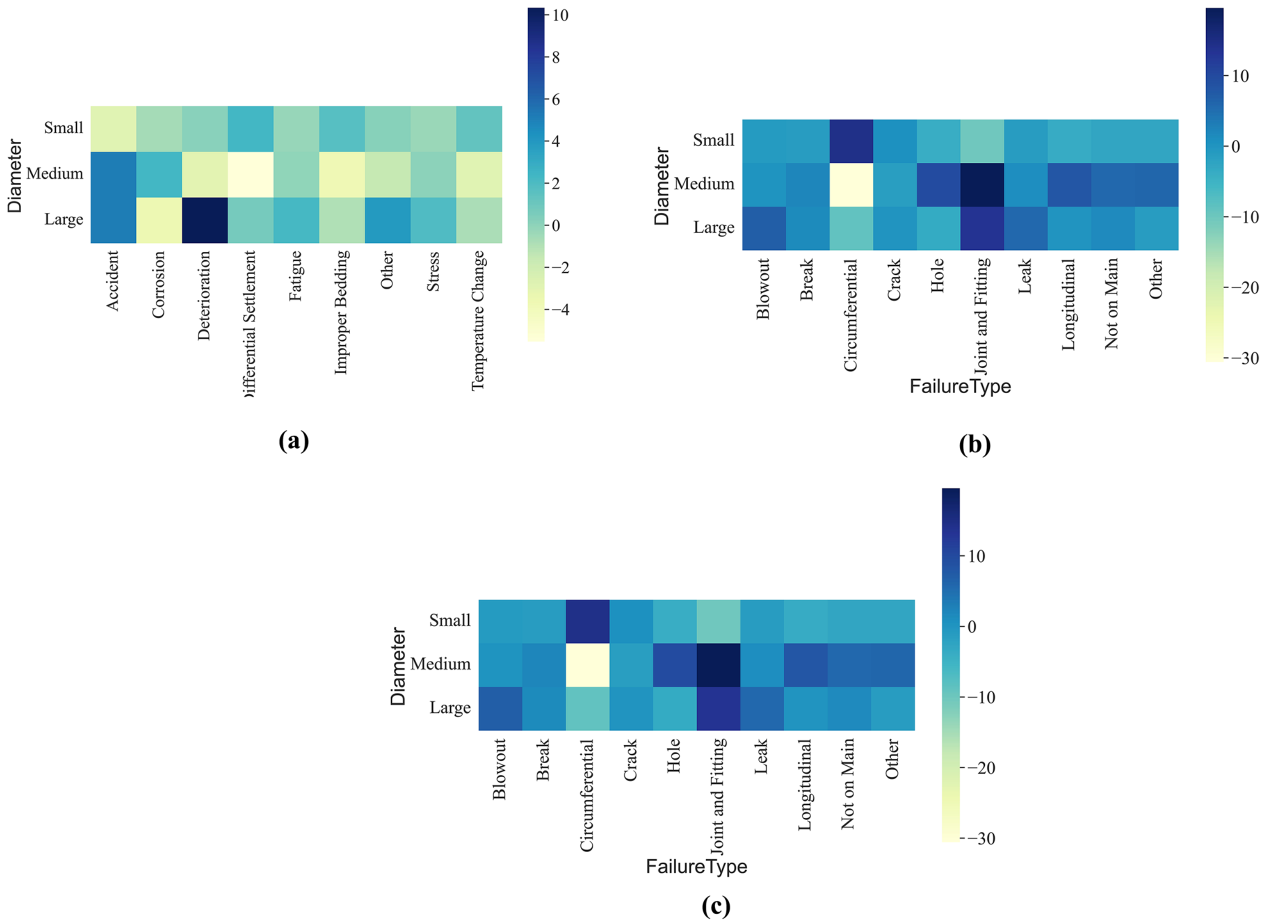

Fig. 11 Association between diameter and **a** failure cause (n = 10), **b** failure type (n = 11), and **c** failure month (n = 11)

While previous studies have analysed failure rates (Barton et al. 2019) and types (Rajeev et al. 2015) for different types of pipe materials, diameters, and seasons; analyses for lining, soil and joint types were lacking. Furthermore, by investigating various pipe and systems properties, together with failure type and cause, the present study enables a systematic view of factors driving water main breaks. It should be noted that the findings presented herein are based on correlations and overall associations. While they point to associations between system characteristics and failure types, causes and rates, alone they cannot identify the best strategies for pipe design, maintenance and rehabilitation. Thus, various opportunities for future investigation are suggested.

In the analysis of lining materials, lined cast iron pipes were still found to break due to corrosion. Thus, earlier application of lining, or use of coating or cathodic protection might be recommended. Cathodic protection status was found to correlate with break status (Fig. 9). The present dataset had less information on coating, and no significant correlation was found. Nevertheless, the results indicate that there is an opportunity to develop a systematic strategy to avoid failures due to corrosion, be that by installing early cathodic protection, or lining and/or coating, depending on whether internal or external corrosion is prominent.

According to the analysis of soil types, pipes installed in clay and sand soils are more likely to fail due to improper bedding and differential settlement, respectively. Thus, utilities should carefully manage future pipe installations and replacements in such soils, ensuring that bedding, backfilling, and compacting specifications are met, whether this work is completed by the utility or subcontracted. These specifications may, nevertheless, differ by utility and further exploration is needed to determine best practices.

Among joint types, universal joints were found to be the most likely to lead to joint failure. Furthermore, joint and fitting failures are most likely for pipes aged 20 years or less, pointing to potential installation errors. Therefore, there is an opportunity for utilities

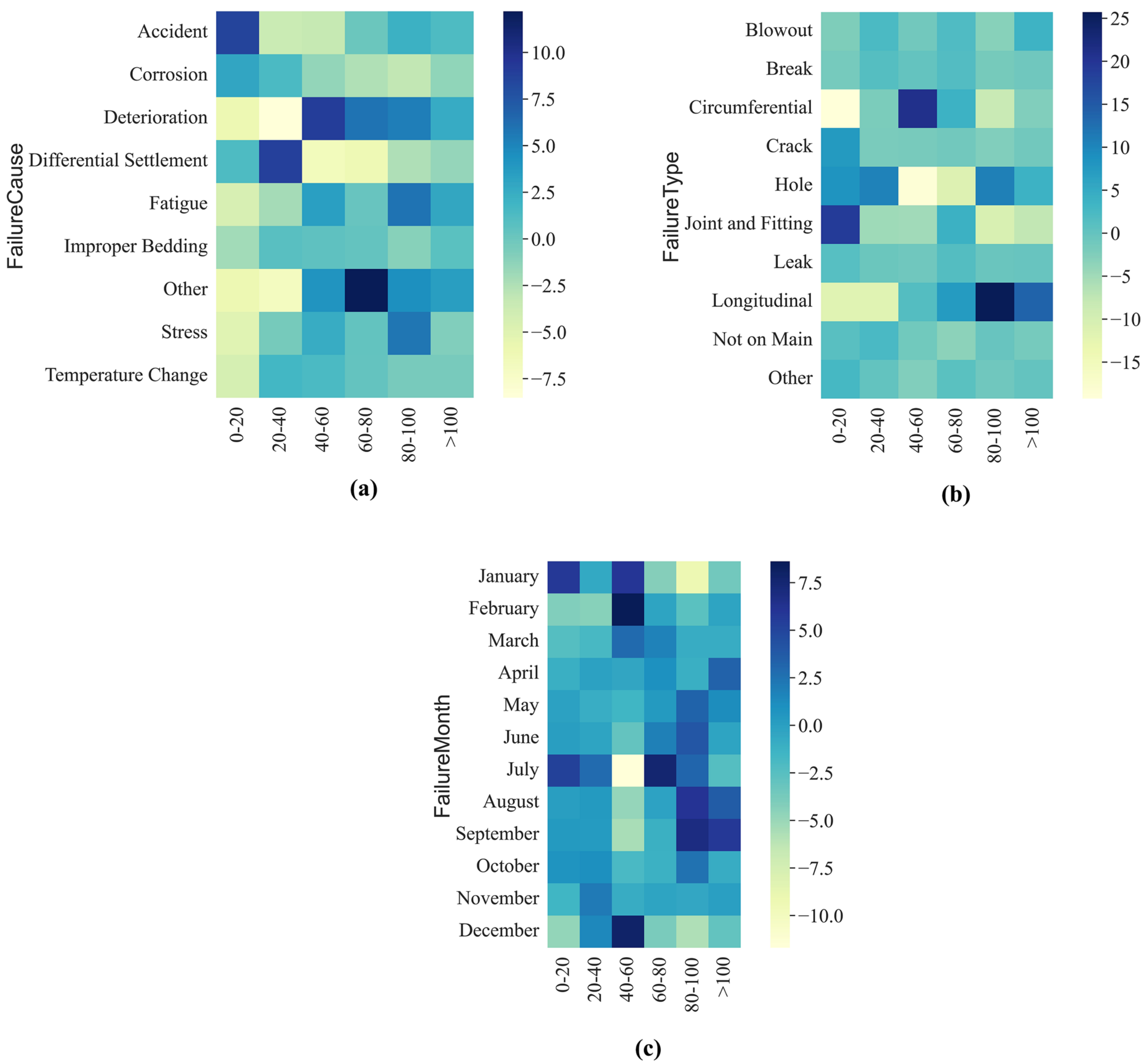

Fig. 12 Association between age and **a** failure cause (n = 10), **b** failure type (n = 11), and **c** failure month (n = 11)

to better manage the installation of joints and fittings, especially universal joints.

The combination of analyses in the present study also enabled the identification of seasonal trends. Peaks in break rates were identified in the winter and summer. In the winter, small diameter pipes are more likely to break, confirming previous findings on the impact of freeze and thaw (Bruaset and Sægrov 2018). In the summer, pipes with collar joints, which are more rigid, are more likely to break. While increased break rates had already been observed in the summer in previous studies (Wols and Van Thienen 2014), the specific fragility of collar joints in this scenario is novel. Additional unique findings related to summer breaks, include the greater likelihood of accidents on AC pipes, and breaks of coal tar lined pipes. These insights into trends can support better maintenance and rehabilitation planning, reducing costly reactive work. They can also inform future cost-efficient design, i.e., selection of pipe material, joint types and lining types. The trade-off between increasing investments in design and maintenance versus reducing risks would require further exploration.

The findings of the present study and similar studies are limited by data availability. Certain attributes, such as roughness, dead-end, and pressure, were collected by only one or two utilities. Their impact on failures requires

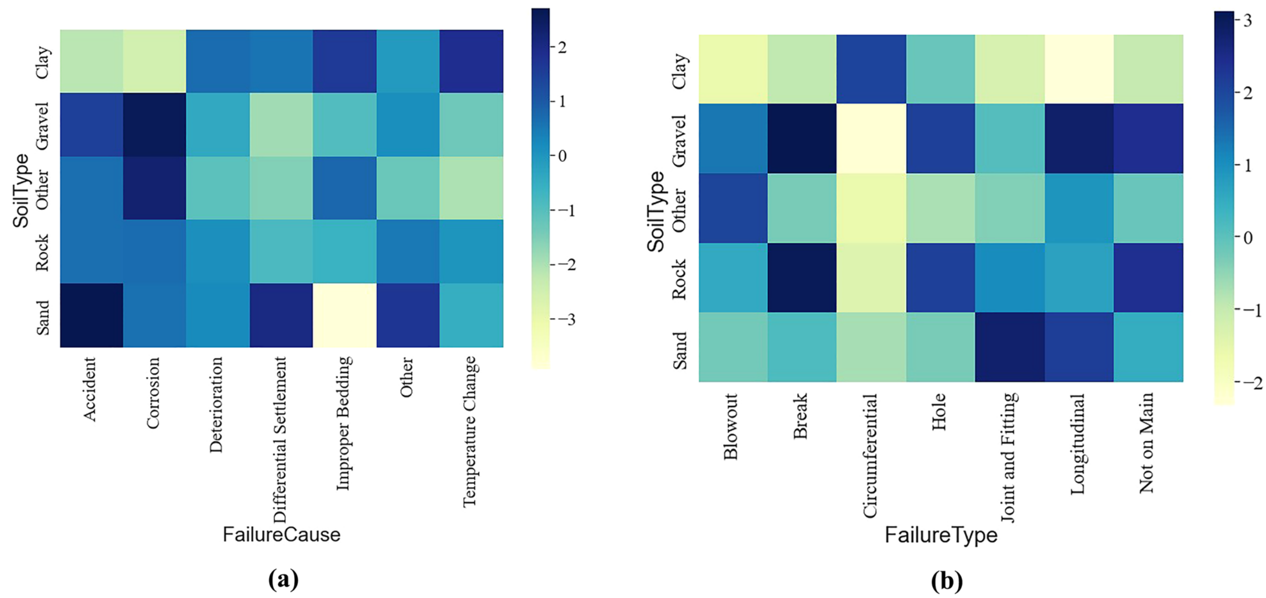

Fig. 13 Association between different soil types and **a** failure cause (n = 2) and **b** failure type (n = 2)

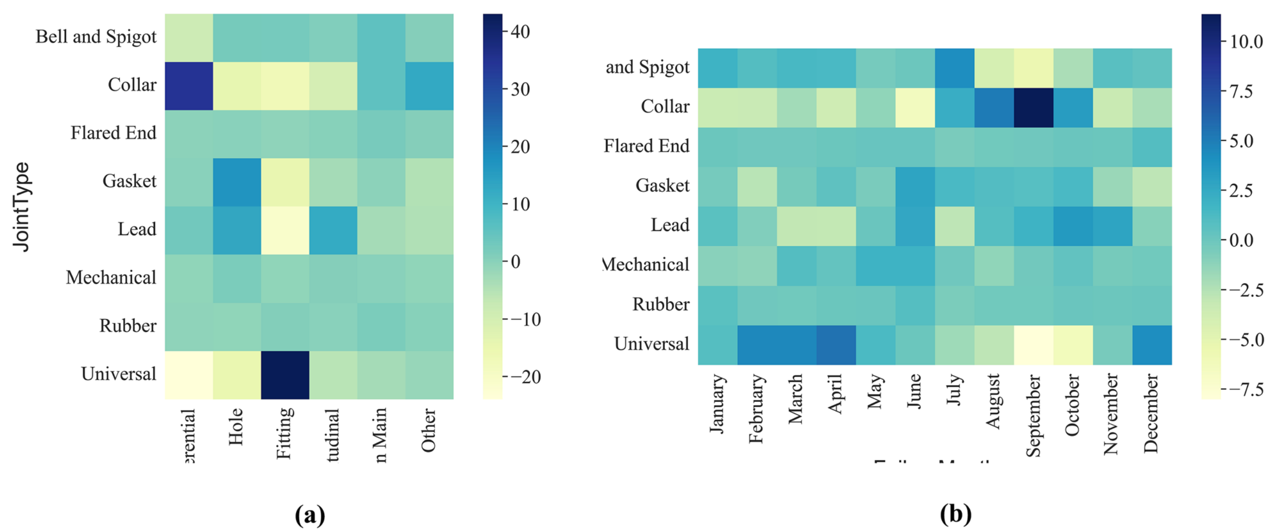

Fig. 14 Association between different joint type and **a** failure type (n = 2) and **b** failure month (n = 1)

further investigation. Other attributes, such as soil type, were collected for broken pipes only. Thus, their correlation to break status could not be analysed. Furthermore, some historical data was lost by utilities. Many utilities use the same pipe ID after a pipe is replaced, overwriting information on previous pipe characteristics. This caused mismatches between information in the inventory and the break dataset. Assigning a new pipe ID and recording the old pipe ID is recommended to ensure all data is maintained.

High quality data depends on consistent and formalized data collection practices. Categorical data was collected with different classes for each utility. Standardizing material, joint type, protection, failure and soil classes would facilitate internal data collection as well as external data-sharing and collaboration. In particular, the failure cause and failure type attributes were often recorded as full sentences by utility operators on site. Thus, the interpretation of the failures is subjective, not only varying across utilities but also among operators of the same utility. The

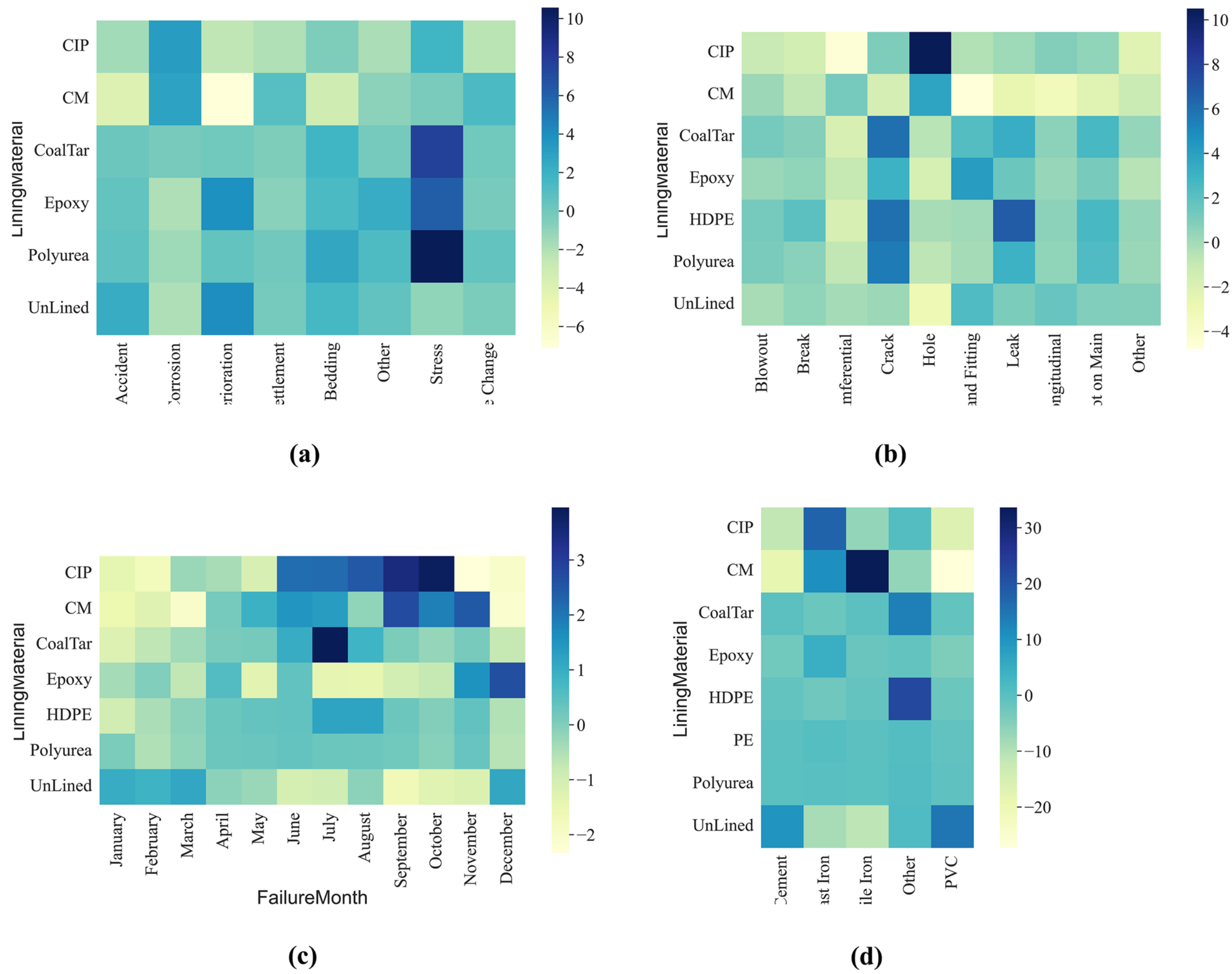

Fig. 15 Association between different lining material and **a** failure cause (n = 6), **b** failure type (n = 7), **c** failure month (n = 7), and **d** material (n = 8)

development of standard definitions and categories of failure cause and failure type is also recommended.

Conclusions

The present study examines the relationship between specific system properties and break characteristics, across thirteen Canadian utilities. Correlation results indicate that current rate of failure is most related to previous rate of failure and age. On the other hand, break status is most associated with material, length, cathodic protection status, cathodic protection age, failure month, pipe roughness, joint type, lining status and lining material, in descending order. There are, thus, multiple factors that can trigger and prevent failure.

Findings from the chi-squared analyses identified unique associations between joint type and lining type, and failure characteristics. Joint and fitting failures are most likely for pipes aged 20 years or less, and universal joints are most associated with joint failure. Furthermore, in summer, pipes with collar joints and coal tar lined pipes are more likely to fail. By analysing failure type and cause, other unique associations were also found. During the summer, accidents on AC pipes are more common. And, in general, pipes in clay and sand soils are more likely to break due to improper bedding and differential settlement, respectively.

The insights provided by the present study can lead to improvements in the design, installation, maintenance, and rehabilitation of water mains. The associations between failures and pipe materials or joint types can inform future designs, so selections are made that extend pipe service life. Improved joint installation practices can reduce early water main failures. Better control of bedding, backfilling and compaction will minimize soil movement and related failures. Preventative maintenance of break prone pipes with collar joints and coal tar lining can reduce costly reactive repairs. More accurate pipe location data and contractor education could also reduce accidental breaks. Overall, these findings highlight a systematic approach to investigating and managing water main failures.

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Author contributions
SG cleaned and analyzed the data, produced graphs, and wrote the manuscript. RD collected the data, reviewed the results and the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from the 13 participating Canadian utilities, members of the Canadian Infrastructure Benchmarking Initiative, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the 13 participating Canadian utilities.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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