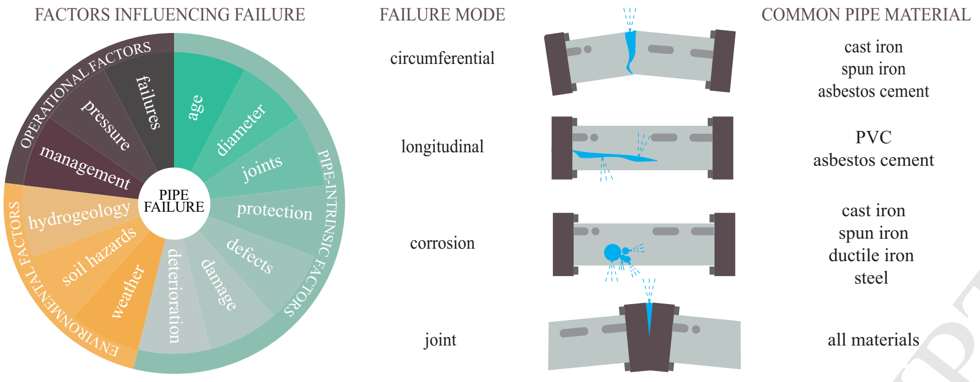
FACTORS INFLUENCING FAILURE
OPERATIONAL FACTORS
failures
pressure
management
PIPE-INTRINSIC FACTORS
age
diameter
joints
protection
defects
damage
deterioration
ENVIRONMENTAL FACTORS
hydrogeology
soil hazards
weather
PIPE FAILURE
FAILURE MODE
COMMON PIPE MATERIAL
circumferential
cast iron
spun iron
asbestos cement
longitudinal
PVC
asbestos cement
corrosion
cast iron
spun iron
ductile iron
steel
joint
all materials

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Improving Pipe Failure Predictions: Factors Effecting Pipe Failure in Drinking Water Networks

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ABSTRACT:

To reduce leakage and improve service levels, water companies are increasingly using statistical models of pipe failure using infrastructure, weather and environmental data. However, these models are often built by environmental data scientists with limited in-field experience of either fixing pipes or recording data about network failures. As infrastructure data can be inconsistent, incomplete and incorrect, this disconnect between model builders and field operatives can lead to logical errors in how datasets are interpreted and used to create predictive models. An improved understanding of pipe failure can facilitate improved selection of model inputs and the modelling approach. To enable data scientists to build more accurate predictive models of pipe failure, this paper summarises typical factors influencing failure for 5 common groups of materials for water pipes: 1) cast and spun iron, 2) ductile iron, 3) steel, 4) asbestos cement, 5) polyvinyl chloride (PVC) and 6) polyethylene (PE) pipes. With an improved understanding of why and how pipes

fail, data scientists can avoid misunderstanding and misusing infrastructure and environmental data, and build more accurate models of infrastructure failure.

1. INTRODUCTION

Across the UK water network, approximately 22% of all treated drinking water is lost through water pipe failure (Farrow et al., 2017). The UK water industry regulator challenges water companies to reduce leakage and service interruptions, and to increase sustainability as future demands continue to grow. To reduce UK failure rates (currently ~ 170 bursts/1000 km/year), water utilities manage assets proactively. An area of interest for asset management is the development of quantitative tools, such as physical and statistical models to prioritise pipe repair and replacement. Statistical models correlate historic failures with observed conditions to predict future failures (Clark et al., 1982; Pelletier et al., 2003; Rajani and Kleiner, 2001).

Understanding modes and mechanisms of pipe failure from historical data is useful for predictive modelling as it can prevent illogical errors which arise from purely data driven approaches, which in turn can result in unrealistic assumptions or additional work through measuring the wrong thing. Complications can arise where data limitations are present (for example where a lack of awareness prevails as to the importance of data collection), or from common data handling practices which can omit records and introduce bias, or sparse data ((Lin et al., 2015)). As a result, data errors become more common (Rajani et al., 2012; Asnaashari et al., 2013; Scheidegger et al., 2013). Existing research provides a foundation for developing an understanding of the complex interactions between factors influencing pipe failure, which form mechanisms for failure (Pelletier et al., 2003; Rajeev et al., 2014; Rezaei et al., 2015). Together, this understanding provides a strong logical foundation for data and infrastructure scientists to develop such statistical models.

With a focus on assisting environmental and infrastructure data scientists to improve predictive modelling, this paper summarises extensive existing research on factors influencing multiple mechanisms of water pipe failure from the international literature. The findings are supported by contributions from industry professionals and network data supplied by a UK water distribution network operator (referred to as the utility provider). Information has been provided in Table 1Table 2, offering a foundation to apply future evaluation of individual pipe material failure for statistical modelling. We discuss each of the main pipe materials, constituting the majority of water network in the UK, namely: Iron (including cast and spun), Ductile Iron (DI), Steel, Asbestos Cement (AC), Polyvinyl Chloride (PVC) (collectively Unplasticised, Post Chlorinated and Molecular Orientated Polyvinyl Chloride) and Polyethylene (PE) (medium and high density).

Table 1: Utility provider network data: pipe installation date, length and number of failures by pipe material collected between 2005 and 2018.

Material	Installation range	Total Network length (km)	Total No. of Pipe Failures
I	1881 to 1921	11,735	26,600
AC	1920 to 1941	7,259	14,053
PVC	1960 to 2001	6,126	11,942
PE	1981 to present	10,538	4,356
SDI	1960 to present	1,902	1,067
Total		37,560	58,018

1.1 DRINKING WATER PIPE FAILURE

Industry professionals and published literature use the terms leak, burst or failure when a pipe breaks and water is released. These terms are often synonymously used, and this paper has adopted the term failure throughout. Pipe failures in this context represents all pipe breaks and leaks that occur and require repair (Laucelli et al., 2014).

There are many different modes and mechanisms for pipe failure. Complex relationships between factors and their relative contributions to the failure mechanism are unique for each pipe material and geographic region (Gould et al., 2013; Rajeev et al., 2014). Factors can be categorised to three groups: 1) pipe-intrinsic, 2) operational and 3) environmental. Figure 1 presents the major factors affecting water pipe failure.

Figure 1. Factors influencing the failure of drinking water pipes.

Typical water pipe failure modes include circumferential break, longitudinal split, joint failure, and holes (both blowouts and pinhole leaks) (Farrow et al., 2017). Failure modes are associated with differing forces acting on the pipe. A typical circumferential break is often caused by tensile forces (soil movement or thermal expansion and contraction) and loading (heavy traffic) forces. Longitudinal splits are often caused by transverse and radial forces (e.g. internal water pressure) possibly in conjunction with a pre-existing defects acting as a point of weakness. Joint failures are typically caused by tensile or compressive forces, while holes are typically caused by radial forces in conjunction with corrosion (Hu and Hubble, 2007; Makar et al., 2001). Figure 2 shows different failure modes acting *in situ*.

The main factors influencing pipe failure; 1) pipe intrinsic, 2) environmental and 3) operational are discussed in detail in the following section. Readers seeking a general summary of the important factors influencing failure in each pipe material are directed to Table 3 in the Discussion.

Circumferential break on an asbestos cement pipe.

Longitudinal split on a polyvinyl chloride pipe.

Corrosion pin hole on an iron pipe.

Joint failure (disconnection or gasket failure) on an asbestos cement pipe.

Figure 2. Modes of failure (images courtesy of Anglian Water, 2018).

2. PIPE INTRINSIC FACTORS INFLUENCING PIPE FAILURE

2.1. PIPE MATERIAL

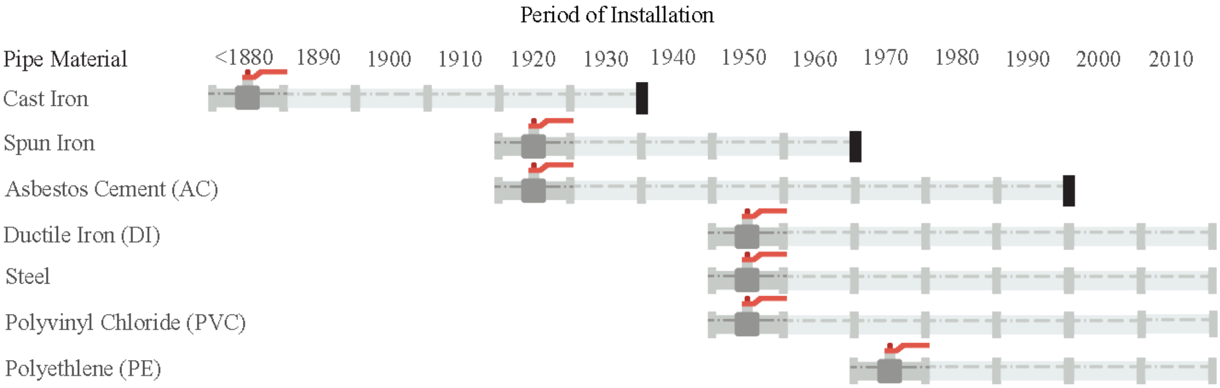


Figure 3. Approximate installation period of drinking water distribution pipe materials in the UK.

Cast iron is one of the oldest pipe materials in the UK, with some pipes dating back even to the mid-1800s (Figure 3). Iron pipes are rigid and had three main manufacturing methods, in sequence: horizontal pit casting, vertical pit casting (cast iron) and centrifugal spinning (spun iron), with each method improving on the former. Cast iron and spun iron pipes are considered together in this review as they have similar failure mechanisms, but are differentiated from the more resilient ductile iron. Ductile iron (DI) and steel were introduced in the late 1950s as alternatives to iron pipes. DI is also manufactured using the centrifugal spun method, but to a stricter manufacturing standards. The material introduces magnesium into the alloy to change the graphite within the microstructure to spheres instead of flakes, producing a tougher material as compared to cast and spun iron. Steel is stronger and more ductile than cast iron, but has a lower tensile strength, and resistance to corrosion (requires more maintenance *in situ* such as cathodic protection) than DI, meaning that DI is preferred for use in diameter pipes typically between 300

– 800 mm in diameter. However, steel is cheaper than DI and its welded joints offer many advantages in high pressure pipes and where working area is limited.As a result, steel is the preferred material for large pipes > 800 mm in diameter (Ductile Iron Pipe Research Association, 1984; Ruchti, 2017; Twort et al., 2001).

UK water companies introduced asbestos cement (AC) pipes as early as 1929 (Van Erp et al., 2015). However, the most prolific period of AC installation was between 1950s and 1960s. AC was cheap to manufacture, cheap to operate (low frictional resistance) and generally resistant to corrosion. However, corrosion did occur in sulphate rich soils or where acidic ground water was present. Al-Adeeb and Matti, (1984) also reported leaching of free lime in pipes that conveyed very soft water. However, AC is a rigid and brittle material and less flexible than DI and steel (Mordak and Wheeler, 1988) so it is less resilient to ground movement. In 1986, manufacturing of AC pipe ceased in the UK due to the negative health perceptions surrounding asbestos in building materials (Twort et al., 2001). By the late 1980s, AC pipes accounted for approximately 11% of the UK's water distribution network (Mordak and Wheeler, 1988).

PVC was introduced in the late 1950s and provided a corrosion resistant and flexible alternative to AC. PVC became popularized in the 1970s, however, during this period the PVC manufacturing process produced low degrees of gelation (where plasticizers diffuse into PVC particles) which resulted in low grade PVC pipes with a low toughness. PVC has rapidly increased in use over the last decade due to improved manufacturing processes (in particular the gelation process), low manufacturing costs, corrosion resistance, and ease of assemblage (Beuken et al., 2012; Bruaset and Sægrov, 2018; EL-Bagory and Younan, 2016; Guoquan and

Yiaoting, 1991). Today, PVC accounts for some 13% of the UK network. By the 1980s, PE was also widely used alongside PVC, but has eventually replaced PVC as it withstands higher pressure and lasts longer. PE remains the material of choice today (Farrow et al., 2017; Ruchti, 2017).

The choice of materials used throughout the timeline is subject to technical considerations, such as material availability, cost, installer experience and skills, ground condition and technician preference to name a few. The extent of pipe material installation in recent years is presented in Table 2.

Table 2: Summary of modern preferred drinking water mains materials (after Twort, Ratnayaka and Brandt, 2001)

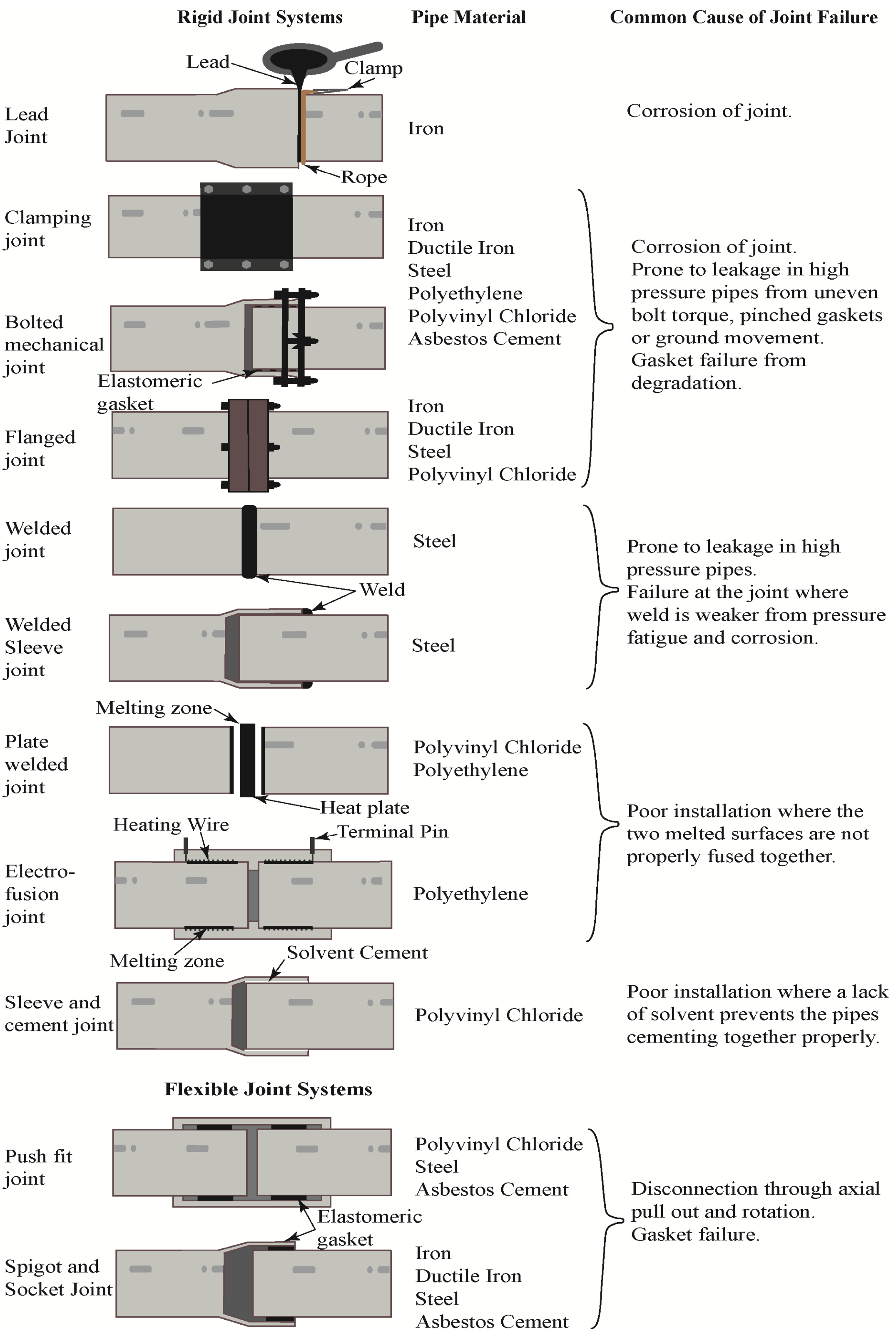
Pipe diameter size (mm)	Material used	Explanation
≤50	PE	Cost effective at small diameters, can be joined easily above ground and placed into narrow trenches.
>50 - <300	PE or PVC DI*	PE and PVC are more cost effective at small diameters, can be joined easily above ground and placed into narrow trenches. Where pressure and diameter increase DI may be favourable due to cost.
>300 - <800	PVC or DI Steel*	PVC or DI are predominantly used and more cost effective in middle diameter pipes. PVC is cheap, flexible and resistant to corrosion. DI is strong and

Pipe diameter size (mm)	Material used	Explanation
		ductile and suitable for many ground conditions. Design and construction is simple due to compatible range of easy assemble fittings.
≥800	Steel DI*	Steel is mainly used for trunk mains or high pressure mains, since welded joints are stronger, provide longitudinal strength and can easily fit in narrow corridors. DI is only used if the price is competitive or no skilled welders are available.

* Less commonly used

2.2. JOINT SYSTEMS

Joint systems are integral to pipe networks, and are considered synonymously with the pipe (Trew et al., 1995). Joint systems can be similar for different pipe materials (such as the bolted mechanical) or can be specific to material type (electrofusion, used only in PE pipes). Today, the most common joints include the spigot and socket, bolted mechanical, flanged, butt welded and push fit (Figure 4). Joint systems are typically sealed with a gasket to ensure a tight seal. Joints systems can be integral (built as part of the pipe) or non-integral (connected separately to two pipe ends). They can be rigid (using flanged or mechanical bolted joints which offer little flexibility) or flexible (push fit or spigot and socket joints which allow the pipe a small margin of movement).



Rigid Joint Systems	Pipe Material	Common Cause of Joint Failure
Lead Joint	Iron	Corrosion of joint.
Clamping joint	Iron Ductile Iron Steel Polyethylene Polyvinyl Chloride Asbestos Cement	Corrosion of joint. Prone to leakage in high pressure pipes from uneven bolt torque, pinched gaskets or ground movement. Gasket failure from degradation.
Bolted mechanical joint		
Flanged joint	Iron Ductile Iron Steel Polyvinyl Chloride	
Welded joint	Steel	Prone to leakage in high pressure pipes. Failure at the joint where weld is weaker from pressure fatigue and corrosion.
Welded Sleeve joint	Steel	
Plate welded joint	Polyvinyl Chloride Polyethylene	Poor installation where the two melted surfaces are not properly fused together.
Electro-fusion joint	Polyethylene	
Sleeve and cement joint	Polyvinyl Chloride	Poor installation where a lack of solvent prevents the pipes cementing together properly.
Flexible Joint Systems		
Push fit joint	Polyvinyl Chloride Steel Asbestos Cement	Disconnection through axial pull out and rotation. Gasket failure.
Spigot and Socket Joint	Iron Ductile Iron Steel Asbestos Cement	

Figure 4. Typical joint systems and failures.

Joint failures include 1) joint leaking, 2) joint fracture, 3) disconnection or 4) gasket failure. Joint leaking can be a result of either poor installation, joint type or ground movement subsequent to installation. Typically rigid joints leak as a result of poor installation such as uneven bolt torque, or pinched gaskets, thermal expansion and corrosion of bolts or connection surfaces (Ruchti, 2017; Twort et al., 2001). However, rigid joints are more susceptible to leakage and joint fracture as a result of ground movements, where multi-directional tensile forces exert stress on the pipe (Farrow *et al.* 2017). Flexible joints are designed to withstand small movement, and are favourable in areas of high ground movement, but multi-directional ground movement or poor installation can result in flexible joint disconnection, (i.e. forcing a straight joint onto two angled pipes). Dingus et al., (2002) and Burn et al., (2005) reported that 15 % and 16 % (average) respectively of all PVC pipe failures were due to joint failure. Kirby (1981) reported that over insertion and angularity of the pipe accounts for 12.4% of all failures in PVC push fit joints. Arsénio et al., (2013) established that disconnection through joint rotation and axial pull out were the most important failure mechanisms for push fit joints (flexible joint) in PVC pipes. This is typically found where the angle of the pipe join increases past 10^o requiring a reduction in joint depth. Gasket failure is a result of age, drying out, loss of elasticity or degradation over time (Farrow et al., 2017). Kirby (1981) established that ~ 11% of PVC failures were attributed to insufficient solvent and poor joint assemblage while 4% arose from the use of excess solvent.

2.3. PIPE COATING AND LINING

Pipe linings (inside the pipe) and coatings (outside the pipe) are used on pipes to slow the corrosion process (Mordak and Wheeler, 1988). Originally iron pipes were installed unprotected, but by the 1900s most pipes were dipped in bitumen to increase their service life. By the 1920s iron pipes were typically lined with cement mortar, which is more resistant to chemical degradation (Ruchti, 2017). Plastic pipes such as PVC and PE are not typically lined or coated due to their resistive properties to corrosion.

All modern DI and steel pipes are reliant on coatings and linings as their very thin walls (typically a few mm thick) are more susceptible to corrosion (Farrow et al., 2017). Linings include bitumen, cement mortar, synthetic resin and galvanisation, whilst coatings include resin or a PE sleeve (Trew et al., 1995). A multi-layered approach is now standard use for steel and DI, including polymer films (epoxy resin) or cement mortar linings, a bonded zinc and water-based paint coat or a mix of zinc and aluminium which acts like galvanisation but makes the surface active in preventing corrosion spreading. In environments that are highly corrosive to steel, additional protection can be included such as cathodic protection (Trew et al., 1995).

AC pipes are typically coated in bitumen, covered in a PE sleeve or coated in epoxy resin of a suitable grade (Farrow et al., 2017; Trew et al., 1995). Due to the natural resistance of AC to concrete corrosion, pipe coatings were only recommended when soils had pH values of less than 6.0, or sulphate between 0.8 – 2.0% (Trew et al., 1995). AC pipes were not often lined, but when required three main types of material were used; firstly coal tar which was replaced by bitumen in the 1920s, and in later years, epoxy resin (Mordak and Wheeler, 1988). The performance of a pipe will be impacted by the type of lining or coating applied, so this information will be of interest to infrastructure modellers.

2.4. MANUFACTURING DEFECTS

Defects introduced during manufacturing increase the probability of pipe failure. Defects in pit cast iron include: 1) non-uniform wall thickness, 2) porosity, 3) inclusions, 4) cold shuts and 5) micro-cracks (Trew et al., 1995) (Figure 5). Non-uniform wall thickness is a result of rising slag and off-centre inner core moulds, causing localised weakened areas of pipe wall. Porosity is caused by air trapped in the mould when the molten iron solidified, causing micro-crack formation paths. Inclusions are objects unintentionally introduced into the material fabric, breaking continuity and causing subsequent weak points. Cold shuts are discontinuities in liquid streaming, resulting in incomplete fusion of two adjoining surfaces. Micro-cracks (longitudinal or transverse) are caused from uneven temperatures (i.e. during cooling), forming weak points from which larger cracks formed under pressure (Makar et al., 2001; Rajkolhe and Khan, 2014; Thacker and Scholar, 2015).

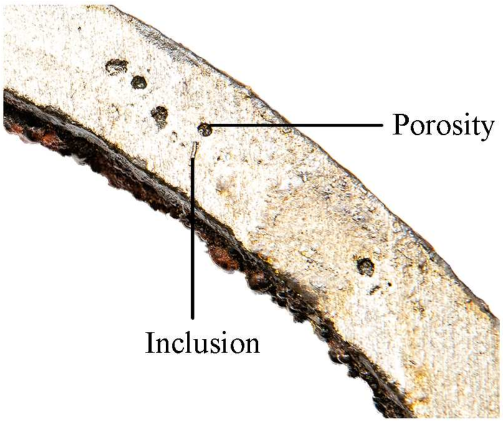


Figure 5. Porosity and inclusion defects in a cast iron pipe.

Spun iron, ductile iron and steel manufacturing processes create an even wall thickness, but common defects such as inclusions, porosity, cold shut and micro-cracks are still present. Steel also can develop defects from insufficient welding along the pipe tongue (Farrow et al., 2017).

Uneven distribution of asbestos fibres in the cement matrix is the main defect in AC pipes. This results in pipe fracture where the pipe strength is weakened (Davis et al., 2008).

PVC, like metal pipes, can have inclusions or porosity issues. Early PVC pipe (up to 1986), are considered to be low grade, often failing due to crack propagation from inclusions introduced during manufacturing. Poor gelation in early pipes (1970s -1980s) also resulted in low resistance against crack propagation. Breen, (2006) investigated PVC lifespan in the Netherlands and reported an optimal gelation range of 60-85% of the pipe wall for high toughness. Some pipes produced in the 1970s had a gelation of < 40% of the pipe wall whilst the 1980s was 50-60%. For later PVC pipes with high levels of gelation (high grade) the main defects are micro-cracks present in pipes as a result of mechanical loading and environmental factors during manufacturing (PVC can become brittle during manufacturing if the temperature is not high enough). Micro-cracks may result in slow crack propagation and eventual failure under cyclical pressure (Restrepo-Flórez, Bassi and Thompson, 2014; Awaja *et al.*, 2016).

2.5. PIPE DAMAGE FROM HANDLING, STORAGE AND THIRD PARTIES

Poor pipe handling can cause invisible dents, cracks, and chips in protective coating. For example, DI is thin and light and easy to dent if moved with excessive force, and fragile coatings on many pipe materials are easily chipped (Farrow et al., 2017). Cracks formed due to careless handling have been observed in AC and plastic pipes, but are not as typical as those on metal pipes. Installation issues also arise from poor storage, improper bedding and poor pipe assemblage. Storage is a specific issue for PVC, as exposure to ultraviolet light for long periods of time embrittles the material. Improper bedding conditions, as reported by Al-Adeeb and Matti (1984), cause higher failure rates in AC pipes due to bending stresses from inadequate support. Kirby (1981) reported poor bedding as the single largest cause of failure in PVC pipes (13.7% of all failures), where large stones caused point loading, and failures were largely due to a range of poor assemblage (joints, seal faults, over bending, excessive solvent etc.) accounting for 51.4% of all failures in the observed UK network. Ruchti (2017) identified third party construction as an issue, where excavation within the vicinity of buried water pipes is a significant risk, and scraping, moving or unsettling bedding areas can result in eventual failure. Scraping of PE pipes >10% of the wall thickness can also lead to premature failure.

2.6. CORROSION AND CHEMICAL DEGRADATION

Corrosion and chemical degradation deteriorates pipes and affects their material integrity through pipe wall thinning, and functional integrity through pipe displacement affecting joints (Vreeburg et al., 2013). Chemical degradation of metal pipes is well documented (Babovic et al., 2002; Folkman, 2018; Hou et al., 2016; Makar et al., 2001; Rajani and Tesfamariam, 2004; Wasim et al., 2018) and rates of failures vary between geographic region. For example Folkman's (2018) US study found that 28% of all pipe failures were caused by corrosion, with iron pipes having the highest failure rate, whilst Babovic et al., (2002) found 48% of iron pipe failures in a study in Denmark were a result of corrosion. Whilst the literature may vary, it is accepted that corrosion of metal pipes has a significant impact on pipe failure. The mechanism for corrosion depends on soil properties, which differ for each location (Hou et al., 2016), thus highlighting the importance of using localised soil maps and data (Pritchard et al., 2013). Wasim et al., (2018) provides a comprehensive review of literature on soil corrosion on pipes. In summary, corrosion rates are related to the coupled effects of a number of soil parameters, which broadly results in higher corrosion rates when: pH is low, moisture content increases (until a limit is reached and then they decline), soil resistivity is low < 2000 ohm cms, soils are highly aerated (but only when soil moisture is present), high temperatures and high levels of soluble salts. The interaction between soil parameters is complex and will interact differently for each material. Wasim et al., (2018) reported that iron corroded faster than DI and steel, and failures in iron pipes can occur suddenly and result in catastrophic failure, whilst DI and steel typically fail in the form of leaks.

Rezaei, Ryan and Stoianov (2015) reported that many failures occurred in aggressive soils where corrosion initiates and accelerates pipe failure. Karpachevskii, Goroshevskii and Zubkova (2011) found that disturbed bedding and backfill can increase corrosion, where soil aeration and water permeability increased this process. Hu, Wang and Chowdhury (2013) found acidic soils with high concentrations of sulphate increase corrosion rates.

Highly corrosive soils can deteriorate pipes at faster rates, especially for older pipes without protection. Two main types of corrosion occur in metal pipes: 1) graphitization and 2) corrosion pitting (Figure 6). Graphitization, described by Makar, Desnoyers and Mcdonald (2001), occurs mainly in cast iron, and is a key corrosion process that occurs when iron oxide reacts with the graphite in the iron alloy, leaching the iron and leaving the graphite behind. In some cases of aggressive graphitisation all iron is removed, significantly weakening the pipe. (Farrow et al., 2017; Rajani and Kleiner, 2001). Corrosion pitting occurs in all forms of metal pipes, from the presence of sulphate and chloride ions in the surrounding environment, causing deterioration of the pipe material from electrochemical and or chemical action corrosion (Volk et al., 2000).

Figure 6. Cast iron pipe corrosion and chemical degradation.

Two main types of concrete corrosion occur in AC pipes: 1) lime leaching and 2) sulphate attack (Hu et al., 2013). Early AC pipes were manufactured using free lime, which was susceptible to lime leaching in certain soil conditions, being particularly evident when silica was not used (Punurai and Davis, 2017). Lime leaching occurs when external pipe conditions are acidic with a low ion content mobile water source (typically a high groundwater level) (Hu et al., 2013; Silva et al., 2002). In such an environment, calcium hydroxide (a free by-product from manufacturing cement mortar, used to stabilise hydrated silicates) is dissolved out of the cement matrix and into the groundwater (Rozière et al., 2009). Once the calcium hydroxide has leached from the cement matrix, the hydrated silicates in the cement mortar decompose. This results in hole formation within the pipe matrix, eventually leading to a soft material where the cement no longer binds the asbestos (Gong et al., 2016). Lime leaching in pipes can also occur when conveying very soft water (pH >7 and a hardness of < 10 mg/l of calcium and magnesium carbonate) which promotes lime leaching and eventually leads to pipe failure (Al-Adeeb and Matti, 1984). Sulphate attack occurs when sulphate in the surrounding groundwater reacts with the calcium hydroxide in the AC material to form calcium sulphate. The calcium sulphate reacts further in the AC matrix and expands, cracking and breaking the cement. AC failure rates were found to be accelerated in soils containing aggressive ions such as magnesium, chloride and sulphate and where pH levels are less than 6.3 (Hu et al., 2013).

PVC and PE are both resilient to corrosion (Ellison and Spencer, 2016), However, both can deteriorate under the right conditions. Both PE and PVC are vulnerable to organic chemicals from polluted soils and from chlorinated water (Kowalska et al., 2016). Soil pollutants can diffuse through the pipe affecting the quality of drinking water (Holder et al., 2019), whilst chlorinated water as a result of using disinfectants (such as chlorine or hypochlorous acid), deteriorates the wall of the pipe through oxidation, which over time embrittles the material, resulting in crack propagation driven by internal pressure. Oxidative degradation can also occur as a result of spontaneous chemical reaction with atmospheric oxygen (Colin et al., 2009; Ghabeche et al., 2015; Mikdam et al., 2017). PVC can also deteriorate due to abiotic factors (e.g. cold temperatures or exposure to UV) and biotic factors (e.g. soil microorganisms or roots) which can result in brittle fracture as the pipe weakens. Brittle fracture in PVC was reportedly exacerbated in contaminated soil and with internal water with high levels of ‘*active organic* *compounds (e.g. detergents or solvents)'* are present (Trew et al., 1995, p. 257), and after long periods of exposure to UV (Ruchti, 2017).

2.7. PIPE AGE

While pipe age has been reported to have a linear relationship with failure rates, with older pipes being more likely to fail (Wengström, 1993), the relationship is actually more complex. Failures rates can be expcted to be higher in the months immediately following installation, then dropping to a low rate of failure for a number of decades, before increasing with age. Folkman (2018) collected data from 308 water companies in the USA and Canada and reported that the average age of pipe failure is 50 years. Age can also correlate with periods of uniform manufacturing, installation and operational practices (Andreou et al., 1987; Kettler and Goulter, 1985; Wengström, 1993). Figure 7 shows the relationship between failure rates and installation period for the different pipe materials present in the utility providers network.

Failure rates for iron, DI and steel peak for pipes installed during the 1920s – 1940s, AC during the 1940s – 1960s. Both PE and PVC have steady failure rates by age. Iron shows that failure rates increase for newer pipes, up to the 1920s – 40s and then fall again which is unexpected. This could be due to manufacturing, where materials and standards have been manufactured differently, reasulting in different quality of materials (Wols and van Thienen, 2016); early iron pipes were locally cast and had very thick walls Iron pipe standards were then introduced in 1917 with BS 78 1917, where pipes were mainly spun to a specification which produced thinner walls that failed ealier than thicker pipes. Thereafter failure rates fall up to the 1960s, which is due to the shift towards centrifugally spun iron and pipe protection, constructional methods which produced a more resilient pipe or the replacement of these lower quality pipes with newer materials (Wols and van Thienen, 2016). All material failure rates start to improve after the 1940s – 1960s, perhaps due to the age of the installation, improved construction practices and improved protection against corrosion.

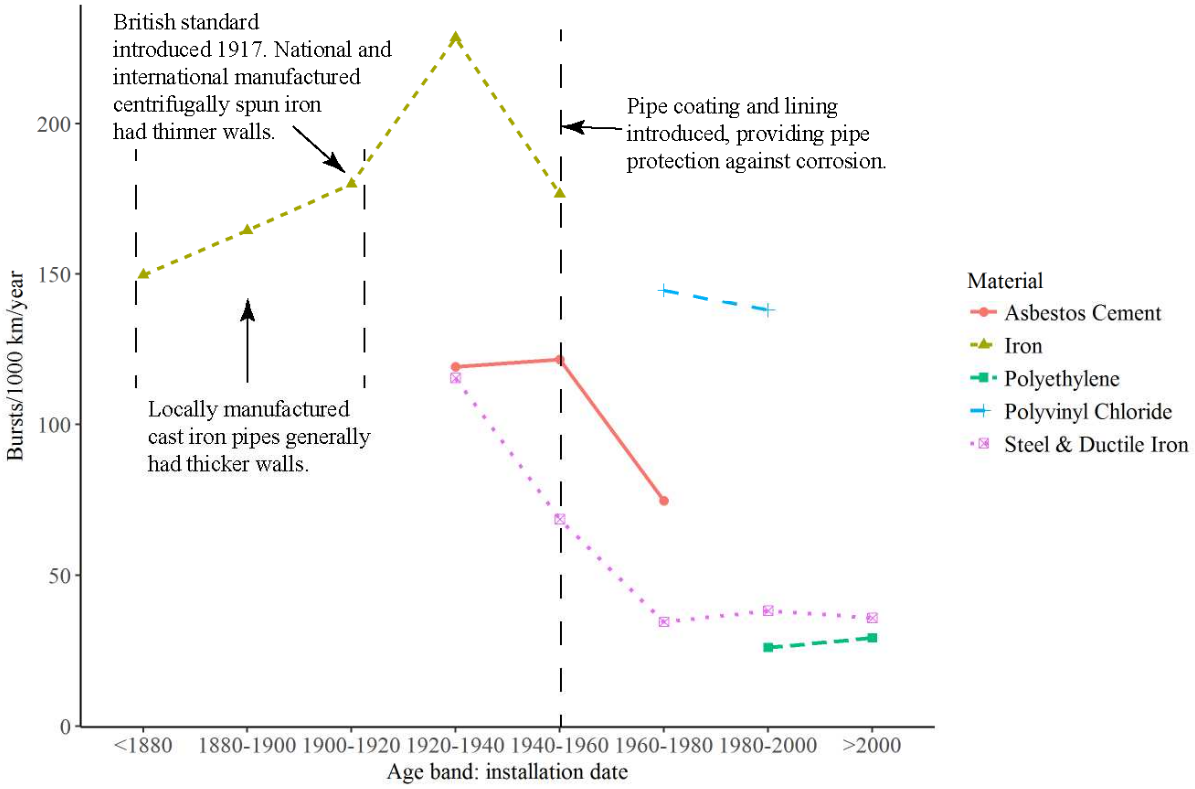


Figure 7. Summary of introduction year and successive failure rates by age by material type (Utility Provider, 2018).

2.8. PIPE DIAMETER

Pipe failure records suggest a strong relationship between failure rates and pipe diameter size (Hu and Hubble, 2007; Kettler and Goulter, 1985; Kimutai et al., 2015; Pelletier et al., 2003). The highest failure rate was reported in pipes < 200 mm in diameter, however, it has regularly been noted that this diameter range is also the most frequent (Bruaset and Sægrov, 2018; Fuchs-Hanusch et al., 2013; Gould et al., 2011; Hu and Hubble, 2007). Higher failure rates in small diameter pipes may be associated with low resilience to ground movement and corrosion (thinner walls), poor joint reliability (Gould et al., 2013) and susceptibility to nearby construction activities especially in urban areas and at shallower depths (Bruaset and Sægrov, 2018). Circumferential failures are typically associated with pipes < 200 mm in diameter, and are the most frequent failure mode for metal and AC pipes of this diameter (Bruaset and Sægrov, 2018; Wengström, 1993). Where longitudinal failures occurred in smaller diameter pipes, Ruchti (2017) reported differential settlement as the common mechanism for failure. When researching large pipes Rajeev *et al.* (2014) found longitudinal failures and holes to be the common failure mode for larger pipes, typically > 300 mm in diameter; the evaluation suggesting corrosion and internal water pressure as the main causes. Typical failure rates by diameter size and material type are presented in Figure 8.

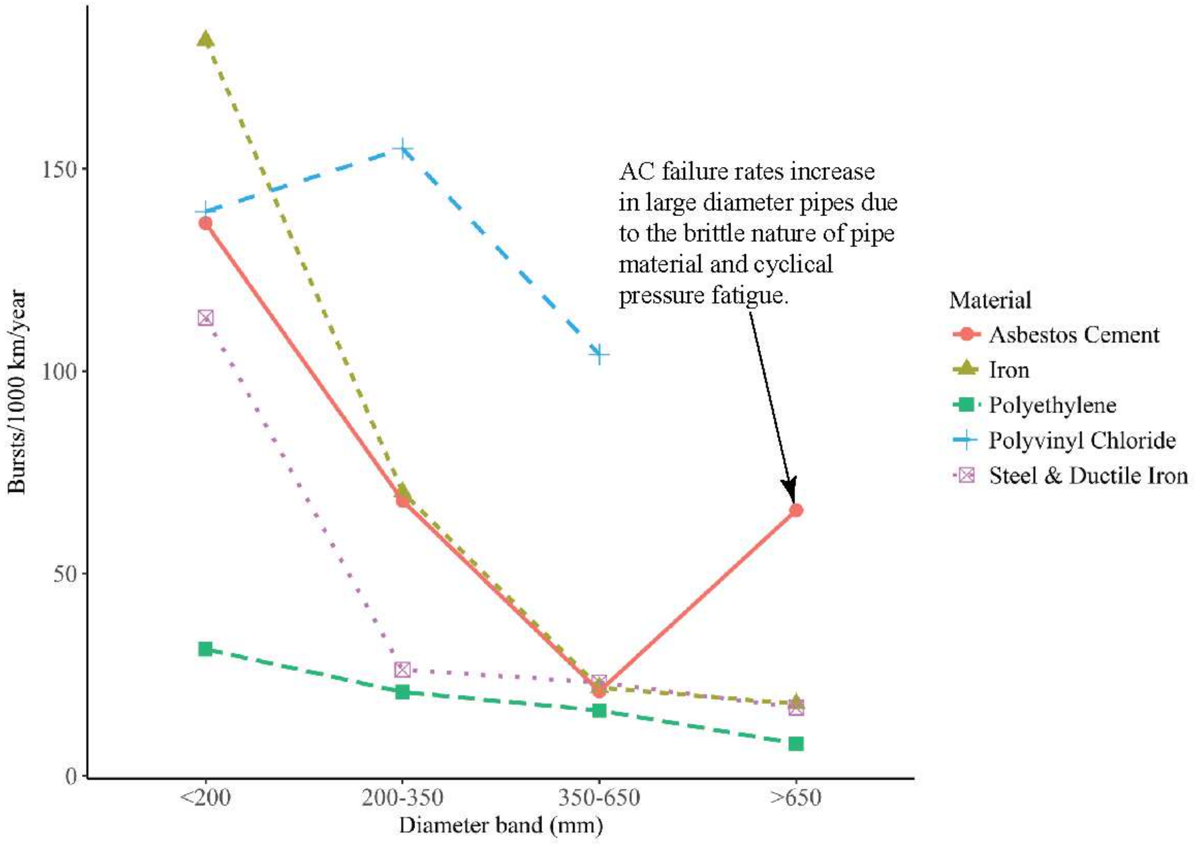


Figure 8. Summary of failure rates by diameter size and pipe material type (Utility Provider, 2018).

3. ENVIRONMENTAL FACTORS INFLUENCING PIPE FAILURE

It is apparent that pipe intrinsic factors have a strong influence on the performance of the pipe. Nevertheless, pipes installed in non-aggressive soils with stable weather conditions will fail less often than those installed in more aggressive soils with highly fluctuating temperatures and levels of precipitation. Thus, predictive models of pipe failure will also perform better with the addition of data on preceding and localised environmental conditions.

3.1. SEASONALITY

Sudden or dramatic seasonal changes have a strong correlation with failure rates (Fuchs-Hanusch et al., 2013; Gould et al., 2011; Laucelli et al., 2014; Pritchard et al., 2013; Wols and Thienen, 2014). Failure rates are higher during dry summers and autumns (typically for AC and PVC pipes) or cold winters (iron, DI and steel), the opposite was observed for wet summers or mild autumn and winters. Fuchs-Hanusch et al., (2013) reported that failure frequency was higher in rigid pipes up to 200 mm during the winter. Andreou (1986) found that circumferential failure is more prevalent in pipes up to 150 mm during the summer. Kottman (1988) reported that season has little influence on pipes at greater depth (> 1 m) and on larger pipes, since they generally fail under high pressure and not ground movement resulting from seasonal weather changes.

A comparison of seasonal failure from the utility provider is shown in Figure 9. The results show that highest failure rates for iron are during the winter months, whilst AC and, to a lesser extent, PVC have higher failure rates during the summer. DI, steel and PE show little variation to seasonal change but can be seen to slightly increase during the winter.

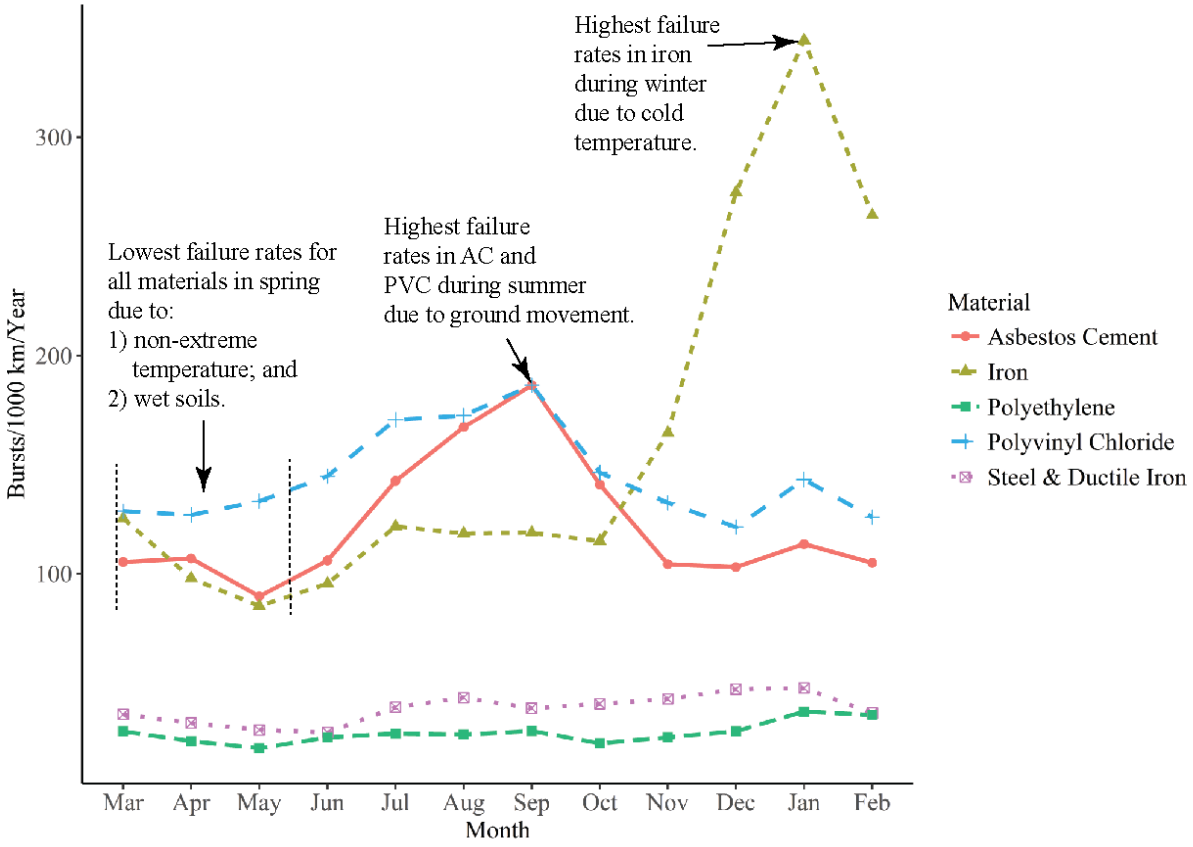


Figure 9. Summary of seasonal failure rates by material type (Utility Provider, 2018).

After reviewing a number of studies considering how weather patterns influence seasonal variations in pipe failure rates, Wols and Thienen, (2014) established the most influential weather factors to be temperature, frost and rainfall deficit (a surrogate for soil moisture deficit (SMD) (Laucelli et al., 2014)), although the effects will vary by pipe material and geographical region (Gould et al., 2011).

3.2. COLD TEMPERATURE

Seasonal pipe failure as a result of temperature has been well documented (Bruaset and Sægrov, 2018; Clayton et al., 2010; Gould et al., 2011; Fuchs-Hanusch et al., 2013; Hu and Hubble, 2007;

Rajani and Kleiner, 2001), concluding that most failures occur during winter months (approximately 60 % (Rezaei et al., 2015)). Wols et al., (2019) observed the effects of weather on pipe failures in the Netherlands, and found that iron, DI, PVC and AC pipes have a varying correlation with cold temperatures. Iron is the most susceptible to cold temperatures below 3^{o}C, and winter failures may be a direct response to the effects of freezing and expansion of soil moisture causing tensile forces and resulting in ground movement and additional compression on the pipe resulting in circumferential pipe failure (Babovic et al., 2002; Kakoudakis et al., 2018; Rajani et al., 1996). Studies in Norway (Bruaset and Sægrov, 2018) and the US and Canada (Folkman, 2018) show that temperatures reach low enough to cause frost heave, which Rajani et al., (1996) report result in movement of trench and side fill. However, in the UK with moderate climates, soil displacement is more likely to occur in the upper soil layer during freezing and thawing (Wols and Thienen, 2014). The highest failure rates found during winter are associated with the first winter frost, where weaker pipes fail, leaving a more resilient network for the remaining winter frosts (Newport, 1981). Subsequent reductions in peak low temperature following the first frost also observes higher failure rates (Habibian, 1994).

The effects of frost are typically seen at depths shallower than 0.5 - 1.0 m below the soil surface depending on frost duration (Pritchard et al., 2013), As guidelines require pipe installation 0.75 m and 1.35 m below the soil surface (Anglian Water, 2014), Habibian (1994) suggests that frost penetration to the depths of buried pipes requires a sustained period of frost. This was also supported by Newport, (1981) who observed failure data from Severn-Trent Water plc. and revealed failure rates for iron increased with deeper frost penetration. Bruaset and Sægrov, (2018) also reported that poor bedding conditions can exacerbate the effects of frost heave.

Summers with long periods of dry weather lead to soil with a low latent heat capacity, which results in deeper frost penetration into the soil during winter (Hu and Hubble, 2007; Laucelli et al., 2014).

Pipe failure due to large temperature differences (Pietrucha-Urbanik, 2015) were observed, or where the temperature dropped and remained low for a long period (a cold snap) (Edil and Bahmanyar, 1983). Farrow *et al.*, (2017) suggest that thermal stress from cold reservoir water can contract pipes, resulting in consequent circumferential fractures, and that this has a higher influence on failure rate during the winter than frost. Rajani, Kleiner and Sink (2012) further observed an increase in failure rate during fast temperature transits for metal pipes below 0^{o}C, suggesting pipes have lower resistance to rapid changes in ground and conveyed water temperature. Rajani and Tesfamariam (2004) reported that where there was a significant temperature difference between internal water (1-2^{o}C) and the external proximal soil (10-12^{o}C), there was a consequent increase in failure rate.

The ability of plastic pipes (PVC and PE) to withstand thermal expansion and contraction (plasticity) means that in general, temperature variation and winter frost has little influence on failure rates (Ruchti, 2017) (Figure 9). However, Wols and Thienen, (2014) reported that PVC pipes have high joint failures during cold temperatures. High joint failure was also reported by Wols and Thienen, (2014) for AC pipes, whilst Hu and Hubble (2007) reported that AC failure rates increased during the winter where long periods of consecutive days' air frost below 0^{o}C were observed. Plastic pipes do not generally fail through frost loading due to their flexible nature, it has been recorded in Canada and the US that pipes can fail where low temperatures cause the internal water to freeze and expand, placing pressure on the pipe (especially where defects are present) (Edwards et al., 2009) – freezing water can expand by 9% in volume. Furthermore, prolonged frost periods can cause increased brittleness in plastic pipes resulting in premature failure (Rezaei et al., 2015). Future trends in climate change suggests that milder temperatures during winter will result in fewer pipe failures during this period, especially in iron pipes (Wols and van Thienen, 2016).

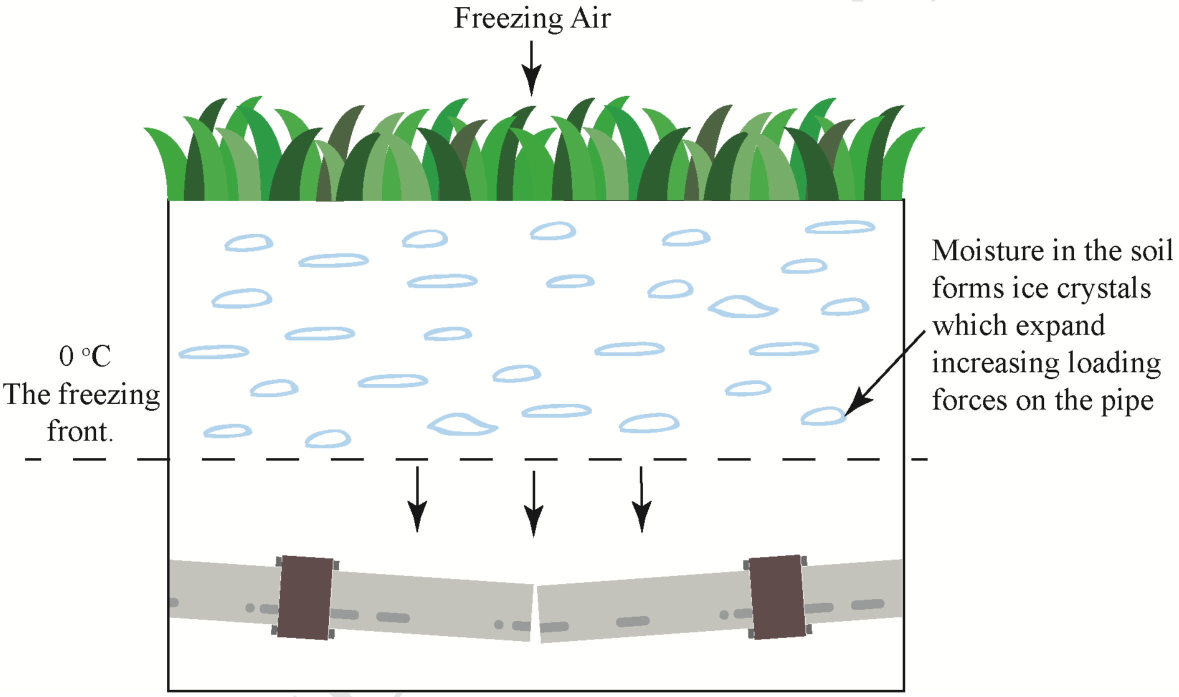


Figure 10. Frost loading on pipe.

3.4. WARM TEMPERATURE AND SOIL MOVEMENT

Soil Moisture Deficit (SMD), represents the difference between soil moisture content and soil moisture saturation. SMD within clay and peat rich soils can lead to shrinkage and swelling resulting in differential ground movement and multi-directional pressure on the pipe resulting in failure (Gould et al., 2011). Farewell, Hallett and Truckell (2012) highlighted the effects of SMD on buried assets, identifying that failure rates are higher in the summer (particularly AC) when SMD is high. Similar findings were reported by Wols and Thienen (2014) but using temperature and rainfall deficit to find drought conditions. The results showed that AC failures increased in the summer months as a result of differential ground movement. Mordak and Wheeler (1988) highlighted that most failures observed for AC during the summer were circumferential fractures, a common failure mode from bending stresses on the pipe or joint disconnection, and Hu, Wang and Chowdhury (2013) observed the same, typically for pipes between 100 - 150 mm in diameter. Alternative suggestions for failures also included thermal stress on the pipe as a result of the difference in temperature between the soil and internal water or longitudinal expansion the pipe (Rajani et al., 1996). Wols and Thienen (2014) found an increase in steel pipe failure during the summer, suggesting thermal expansion at high temperatures on pipes with a reduced resilience (due to degradation) as a potential cause.

Pipe failure is lowest during the spring when soils are consistently wet, so movement is unlikely. Chan, Gould and Davis (2005) suggested that the late summer and early autumn months are the most influential time of year for AC failure rates, since soil moisture and temperature varies the most during this period, increasing the shrink swell effect. This is also shown in the data from the UK utility provider in Figure 9. UK soils normally dry to 1 – 1.5 m (Pritchard et al., 2015a), but long periods of drought can result in deeper drying and higher failure rates (Farewell et al., 2012b). High failure rate in PVC push fit joints are associated with ground movement causing disconnection through joint rotation and axial pull (Arsénio et al., 2013). The effects of soil shrink swell on pipes from changes in soil moisture are shown in Figure 11.

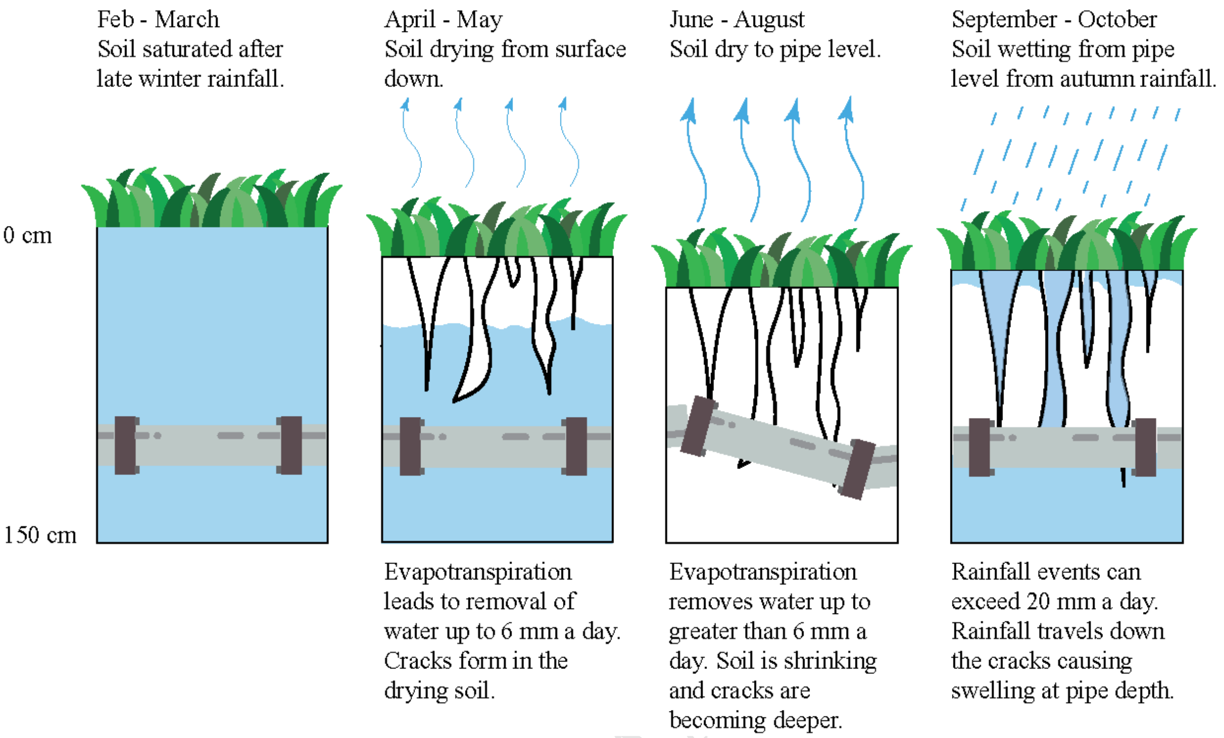


Figure 11. Seasonal shrink swell effect in clay-rich soils (after Farewell *et al.*, 2012, p. 10).

Soil related ground movement represents a hazard to pipes, and depends on soil properties (i.e. texture, structure, porosity) which control moisture transport and storage. Soils are generally considered to be weaker when wetter, and are therefore more prone to movement (Pritchard et al., 2013; Yahaya et al., 2011). Clay and peat soils have fine particles, low permeability and poor aeration which result in high water retention after wet periods (swelling) and high evapotranspiration when temperature is high and rainfall is low, leads to soil shrinkage. Clay and peat soil shrink swell is associated with circumferential breaks and joint failure in pipes, and are typically associated with soils which cause higher rates of chemical degradation to pipes (Hu and Hubble, 2007; Mordak and Wheeler, 1988; Pritchard et al., 2014; Ruchti, 2017).

Patterns of future climate change suggest a bearing on geographical variation in environmental vulnerability to soil-related influences, where prolonged droughts cause increased soil movement (Pritchard et al., 2015b, 2014), and potentially higher failure rates during this period, especially in AC pipes (Wols and van Thienen, 2016).

3.5. OTHER SOIL GROUND MOVEMENT HAZARDS

Other soil related ground movements include peat shrinkage, sand washout, silt ground heave and soft and compressible soils (Pritchard et al., 2013). Sandy soils typically drain water due to their large particle size. Sandy soils that contain particles between 0.06 mm to 2.0 mm are susceptible to wash out and erosion from excessive water flow (i.e. events such as pipe failure) resulting in pipes being unsupported and sagging (Brink et al., 1982). Farewell, Jude and Pritchard, (2018) reported that pipe failures in sandy soil had a spatio-temporal relationship with previous failures, suggesting loss of water under pressure can lead to washout of sandy soils and further failures. They also reported that trenching during construction of roads provides preferential hydrological pathways which can lead to washout cavities in sandy soil conditions. Soft soils such as organic peat (organic soils) have poor bearing capacity due to their generally high retention of moisture, which offers little support to pipes. The result is a sagging, or ‘bridged’, pipe with pressure loading causing failure at the pressure point (Pritchard et al., 2015b).

Differential settlement is the natural compaction of soils which results in the uneven settlement of the pipe. This can be caused by natural soil transition, poor foundation construction or crossing with other utilities (Babovic et al., 2002). The transition of pipes across different soils can result in premature pipe failure, where pipes curve as a result of soft to hard soil transition, especially more rigid pipe materials (Wols et al., 2014). Wols and Van Thienen, (2014) suggests that climate change and potential increase in long periods of drought will increase the effects of differential settlement on pipes.

Once the pipe intrinsic and environment factors are sufficiently considered, the way in which the pipes are operated, managed and used should be investigated. In the authors' experience, it is this suite of operational factors for which it is the most difficult to obtain consistent reliable data over sustained periods of time.

4. OPERATIONAL FACTORS INFLUENCING PIPE FAILURE

While it is recognised in the industry that pipe management and operation is linked to the rate of failure, there it less discussion in the literature on these impacts specifically discussing failure rates. This may be because operational data is less commonly recorded in model-friendly data sets. We discuss common operating factors, but recognise the following as potentially influential to pipe failure: pressure management, flushing events, network changes such as non-return valve replacement, jetting and maintenance, network jobs, fire hydrant testing, water temperature and proximity to high water consumers (e.g. agricultural facilities).

4.1. INTERNAL WATER PRESSURE

Changes in internal pressure can increase the likelihood of pipe failure. Two main influences in changes to internal pressure have been reported to cause early pipe failure: 1) cyclical pressure and 2) transient surge pressure. Cyclical operational pressure from consumer patterns and changes in network operations (pressure management) leads to periods of high and low pressure. Rezaei, Ryan and Stoianov (2015) studied the effects of cyclical pressure on a water supply network and found that cyclic loading can result in fatigue failure if the frequency and magnitude were appropriate. This was especially apparent in pipes with defects where the loading stress can speed up crack propagation resulting in early failure. Wols et al., (2019) reported an increase in AC failure rates during high temperatures and suggested water demand causing high internal pressure or a large pressure difference could be a possible cause. Iličić, (2009) reported for a single district meter area in Zagreb that pressure regulation had a positive effect on reducing pipeline failures by 17%. This was particularly evident in iron and PVC pipes, since joints in these materials have less resilience to pressure oscillations.

Transient surge pressure also known as “water hammer” is caused by a result of network operations such as flushing events, fire hydrant testing, valve changes or pumping station failure. These can cause additional stress on pipes through sudden changes in internal pressure exposing the pipe to the strongest physical load it is likely to experience (Martínez-Codina et al., 2016). Pozos-Estrada et al., (2016) researched pressure on concrete pipes and found that transient pressure over pressurizes the pipe causing catastrophic ruptures of the pipe. Martínez-Codina et al., (2016) reported on a range of pipe materials including metal, cement and plastic, and suggested that medium to high pressure inside the pipe caused during transient surge pressure is one of the common causes of pipe failure in large diameter pipes, and is especially prevalent in pipes where micro-cracks and corrosion have weakened their resilience. The result is loss of integrity or pipe wall through blow outs or joint failure (Boulos *et al.*, 2005; Rezaei, Ryan and Stoianov, 2015). Further to this, it has been reported that the presence of air pockets in pressurised pipelines can greatly exacerbate the effects of transient pressure (Pozos-Estrada et al., 2016).

Boulos *et al.* (2005) reported transient surge pressure as being less likely to affect urban distribution networks due to short pipe length (less than 600 m), suggesting short length of pipes tend to limit the effects of transient surge pressure due to junctions causing pressure wave reflections which dissipate the effects of concussive water hammer. Operation of pumping stations can result in failures where power cuts can cause reverse flow surge, and transient surge pressure introduced after re-joining the pump (Guyer, 2013). Ruchti (2017) highlighted that smaller diameter pipes are less prone to failure than larger pipes from internal pressure, largely due to the low pressures commonly used in such pipes.

4.2. PREVIOUS FAILURES

Previous failures can result in cascading failures where the initial failure can result in a secondary or multiple consecutive failures located spatiotemporally close to the first (Clark, Stafford and Goodrich, 1982). Many statistical models do not account for this phenomenon despite previous studies suggesting its importance (Scheidegger et al., 2015). Goulter and Kazemi (1988) revealed that 22% of failures occurred within one meter of the previous failure and 42% of these failure occurred within 1 day of the first failure. This pattern is typically attributed to the aging deteriorating pipe and the potential for the first failure to disturb the surrounding environment through washing and eroding bedding conditions, altered soil moisture conditions weakening soil and the disturbance of the pipe during repair operations (Farewell et al., 2018; Farrow et al., 2017).

5. DISCUSSION

The failure modes and mechanisms of water distribution pipes are complex, varying across geographical locations and by pipe material. Factors that increase the chance of failure are often interconnected, and thus typically no single failure mechanism is uniquely related to one factor. However, certain factors emerge as having a greater influence than others for each failure mode. Table 3 shows a summary of the failure modes and mechanisms by material type.

Table 3: Summary of the failure modes and mechanisms by material type.

Material	Mechanism			Typical Failure Mode
	Pipe - Intrinsic	Environmental	Operational	
Iron	Pipe diameter. Manufacturing defects. Graphitization. Pipe protection. Rigid joints. Construction and repair – accidental damage.	Cold temperatures. Frost. Cold internal water temperature. Highly corrosive soils.	Cyclical pressure fatigue. Transient pressure. Management operations.	Circumferential break. Joint failure. Longitudinal failure. Chemical attack.
Steel and Ductile	Thin pipe wall. Manufacturing	Highly corrosive soils.	High pressure. Cyclical pressure	Chemical attack. Joint failure.

Material	Mechanism			Typical Failure Mode
	Pipe - Intrinsic	Environmental	Operational	
Iron	defects. Pipe protection. Rigid joints.		fatigue.	
AC	Pipe diameter. Manufacturing defects. Pipe protection. Rigid joints.	Warm temperatures. Low rainfall. Fluctuating soil moisture. Clay and peat soils – shrink swell potential. Highly corrosive soils.	High pressure. Cyclical pressure fatigue.	Circumferential break. Joint failure. Chemical attack. Longitudinal failure.
PVC	Poor joint assemblage – solvent. Storage – UV light exposure Manufacturing defects. Loading –	Warm Temperatures. Low rainfall. Fluctuating Soil Moisture. Clay and peat soils – shrink swell potential.	High pressure. Cyclical pressure fatigue.	Joint failure. Longitudinal failure.

Material	Mechanism			Typical Failure Mode
	Pipe - Intrinsic	Environmental	Operational	
	sensitivity to point loads.	Sandy soils – wash out		
PE	Poor joint assemblage.	-	-	Joint failure. Longitudinal failure.

Iron pipes have a high failure rate during the winter as a result of low temperatures and frost, which results in freezing soil moisture and expansion of soils, causing circumferential failures or joint failure (especially in rigid joint systems). This results in failure in the less resilient pipes (those affected by highly corrosive soils). Corrosion is a major factor in iron pipe failure, particularly before coating was introduced or where the coating was damaged during installation. Corrosion from soils causes thinned pipe walls which results in pin holes and small leaks in small diameter pipes, to blowout holes in larger pipes if high pressure is reached. Longitudinal failures in iron pipes are less common, but typically, result from defects in the manufacturing process which leads to micro crack propagation and eventual failure. As corrosive soils also tend to be shrinkable, the ground movement associated with summer and autumn can also break weakened pipes.

Steel and Ductile Iron have a low failure rate, but are prone to corrosion holes in pipes and potential blowout holes in large pipes with high pressure. Rapid corrosion in the thin walls can occur when the protective coating is damaged. Seasonal weather variation does not appear to strongly impact the failure rates of these pipe materials.

AC pipes largely fail during the summer months as a result of differential ground movement. Ground movement causes multi-dimensional stress on pipes which lead to eventual failure of weakened pipes, especially those with manufacturing defects and pipes which have been deteriorated by highly corrosive soils. The main factors affecting AC pipes include seasonally fluctuating temperatures, and rainfall leading to large changes in soil moisture, and associated shrink-swell, in clay rich soils. Circumferential failure is the most common mode of failure accounting for approximately 75% of all failures, being typically associated with pipes < 200 mm in diameter due to thin walls and low resilience to bending especially when weakened by chemical attack.

PVC pipes have a higher failure rate during the summer and the majority of failures occur from joint failure. This is a result of differential ground movement which results in joint disconnection through joint rotation and axial pull out in push-fit joints and poor assemblage. Poor bedding conditions, such as coarse rock, may cause pressure points on PVC pipes and can lead to longitudinal failure starting from the pressure point. Cyclical pressure fatigue can cause longitudinal failures in pipes with manufacturing defects, where micro cracks propagate quickly, or where the pipe becomes brittle from the effects of UV light during storage.

PE pipes have very low failure rates and are resistant to corrosive soils, ground movement, weather conditions and pressure changes from operational management. For these reasons, they are widely used in new development and asset upgrade. Most failures on PE pipes come from poor construction of joints, since specialist training is required for the electrofusion fitting.

There exists a wealth of information in existing literature that can be used by data scientists to explore pipe failures using statistical models. The information presented here can be used to guide initial exploratory investigations to ensure that relevant data inputs and modelled outputs are consistent with existing understandings of typical modes and mechanisms for pipe failure. Operational factors are very important, but data is still inconsistent and incomplete across large networks (e.g. pressure is still largely modelled, rather than measured across much of the UK water network). As this situation improves, it is highly likely that recording operational data across entire water networks in a consistent manner over many years will give rise to improved predictive models of pipe performance in the future. Modelling of the impact of management decisions, investments and public engagement schemes will become an important area that requires further investigation.

6. CONCLUSION

There are a wide variety of factors which increase the likelihood of pipe failure. Pipe failures are more likely on older less resilient pipes, in aggressive soils where weather and operational conditions are extreme and unstable. Sudden changes in temperature, pressure or soil moisture levels will increase internal and external stresses on pipes, increasing the chance of failure.

When building data-driven, statistical models of pipe failure, it is important to obtain a basic understanding of the common mechanisms of pipe failure. When this step is overlooked, data can be misused through misunderstanding (especially common is the confusion of correlation and causation). Sense-checking models, and their data inputs, against modes and mechanisms of failure reported in the literature will help ensure that data driven models of pipe failure are robust and fit for purpose. Such models, in turn, can lead to actionable information which utilities can use to improve the performance of this critical national infrastructure and meet the water demands of a growing population under a more extreme climate.

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HIGHLIGHTS:

- Pipe failure models can be improved with an understanding of failure mechanisms
- Examples of failure data from the literature is supported by a large water utility's failure data
- Pipe failure modes are summarised for common pipe materials
- Environmental, operational & pipe intrinsic factors impacting failure are discussed
- Summaries are provided for key failure mechanisms for common pipe materials

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: