Factors influencing corrosion of metal pipes in soils

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REVIEW

Factors influencing corrosion of metal pipes in soils

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Abstract

Deterioration of buried metal pipes due to corrosive soil environment is a major issue worlwide. Although failures of buried pipe due to corrosive soil is an old problem, yet such failures are still uncontrollable even with the application of advanced corrosion protection technologies. Therefore, understanding factors causing corrosion of buried pipes is necessary. This article reviews factors causing corrosion of buried pipes in soils. Factors include moisture content, soil resistivity, pH, dissolved oxygen, temperature and microbial activity. Moreover, we discuss the influence of manufacturing method and the comparison of corrosion behaviour of cast iron, ductile and mild steel pipes. We found that corrosion rate of pipes increases with moisture contents up to the critical moisture value. Although pH affects corrosion, there is no relationship between corrosion and pH and the corrosion rates of buried pipes are inversely proportional to soil resistivity. Soils containing more organic matter show high resistivity. Dissolved oxygen in soil develops differential cell which accelerates corrosion of metallic pipe. Different types of bacteria present in soil develop biofilms on metallic pipes, which deteriorates pipes with time.

Keywords Corrosive soils · Ferrous metal pipes · Manufacturing methods · Bacterial corrosion · Simulated soil solution · Electrochemical evaluation

Introduction

Failures of buried pipeline systems (water, sewage, oil and gas) due to corrosion are an inevitable concern for owners and asset managers in any country, as they reduce the service life of pipelines. Sudden bursts of pipes and the consequent significant losses have been reported on news channels and in newspapers in well-developed countries. These pipes are buried underground, which makes their inspection and maintenance difficult in any specific location, in addition to field conditions and environmental changes. The high frequency of pipe failures indicates the lack of understanding and inaccuracy of current theories used for the prediction of failure of buried pipes. Although comprehensive research related to the corrosion failure of cast iron pipes has been conducted in various countries of the world funded by local research councils, for example, the Australian Research Council (Australia), the National Science Foundation (USA), the Engineering and Physical Sciences Research Council (UK) and the National Research Council (Canada), these failures are still unavoidable.

Pipelines are designed for more than 50 years of service life which can exceed 100 years (Belmonte et al. 2008), but they fail before this service life. Ageing, long service, damage to protective coatings internally or externally, improper repair and maintenance lessen the service life of buried pipes. In Australia, the failure rate is 20 breaks per 100 km per year on average and the replacement cost has increased by 10% annually since 2006 (Hou et al. 2016). From this statistics, it is apparent that pipe failure is a global issue with severe socio-economic impacts. The occurrence of these failures is sudden without any warning. The situation becomes even worse when the reoccurrence of such failures

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happens, which indicates the inadequacy of current knowledge related to the failure of buried pipes.

Comprehensive field research on corrosion of pipes revealed that soil's corrosive environment is the root cause of failures of buried pipes (Malvin 1958; Kleiner and Rajani 2001; Romer and Bell 2001; Atkinson et al. 2002; Alamilla et al. 2009; Cole and Marney 2012; Asadi and Melchers 2017; Qin et al. 2018). For example, according to comprehensive surveys undertaken by the American Water Works Association (USA), almost 70% of buried ferrous metal pipes fail due to the corrosive soil, as shown in Fig. 1 (Romer and Bell 2001). A similar situation exists in different parts of the world, including Canada, UK and Australia (Cole and Marney 2012). The corrosive soil reacts with the exterior surface of buried pipes, which in turn results in the corrosion of pipes. Despite previous and the latest research (Malvin 1958; Makar and Rajani 2000; Kleiner and Rajani 2001; Romer and Bell 2001; Grigg 2006; Moglia et al. 2008; Dehghan et al. 2008; Gould et al. 2011; Pelletier and Allaire 2003; Sadiq et al. 2004; Asadi and Melchers 2017), which has identified the factors influencing external corrosion of pipes, researchers are still trying to find the causes and their remedies for the external corrosion of pipes.

Therefore, in-depth knowledge of factors causing external corrosion of pipes in soils is necessary. This paper presents a review of the current understanding of underground corrosion science and the leading causes and factors influencing the corrosion of buried pipes in soils. The influencing factors in soils that are reviewed in this paper are pH, moisture content, temperature, resistivity, differential aeration, soil type, soil particles and permeability, and the presence of sulphate-reducing bacteria. The approaches adopted to investigate these factors both in the field and in the laboratory, the findings, limitations and gaps in the previous studies are thoroughly reviewed in this paper. The factors which are comprehensively reviewed in this paper are encapsulated in Fig. 2. Corrosion mechanism of a pipe buried in soil is demonstrated in Fig. 3. Moreover, the method of manufacturing adopted for different types of ferrous metal pipes i.e., cast iron, ductile and steel, and the comparison of their corrosion behaviour in the soil are also reviewed and discussed in this paper. Further, the updated review of the corrosion studies conducted using simulated soil solutions is also presented in this paper.

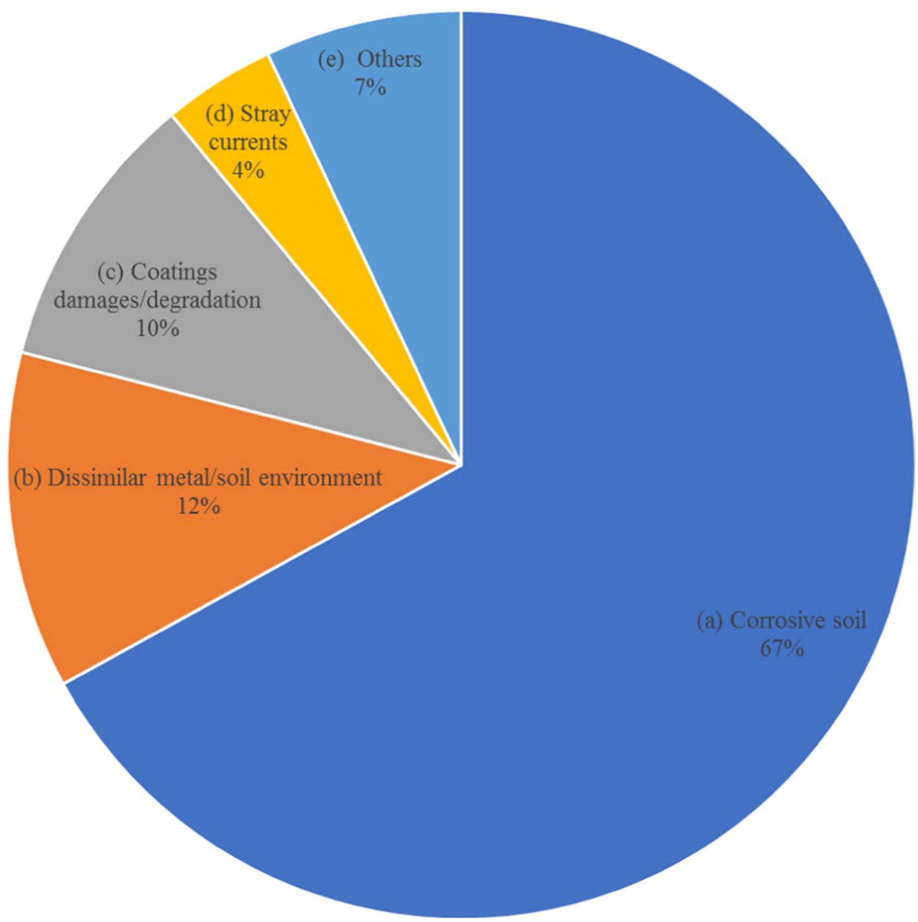


Fig. 1 Reported causes of corrosion of buried pipes. It is reported in the literature that major factor that contributes to corrosion of metal pipes is soil corrosiveness. Soil corrosiveness is increased by the presence of sulphates, chloride, moisture and bacterial activity. Redrawn, originally by Romer and Bell (2001)

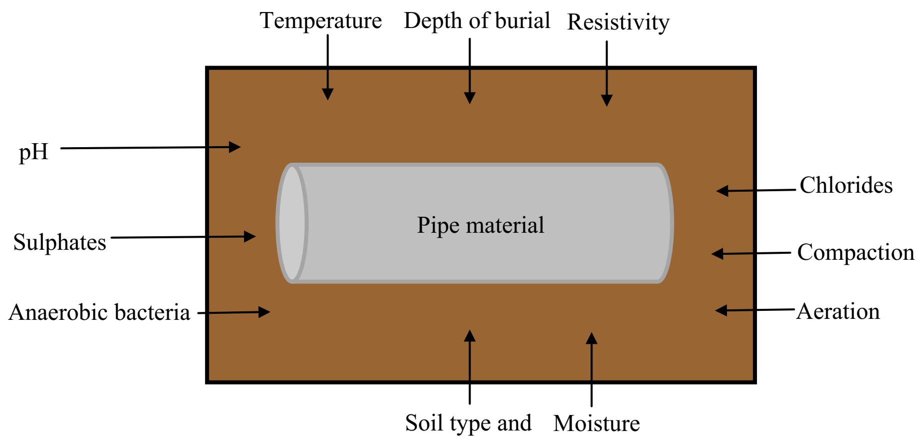


Fig. 2 Key factors affecting external corrosion of buried pipes. Some of these factors are dependent on each other. Soil resistivity has a direct relationship with moisture content and chloride concentration. As moisture contents and chloride concentration increase, soil resistivity decreases. Aeration of soil can be changed by the rain and the bacterial activity. pH of the soil is affected by acid rain and acid-producing bacteria

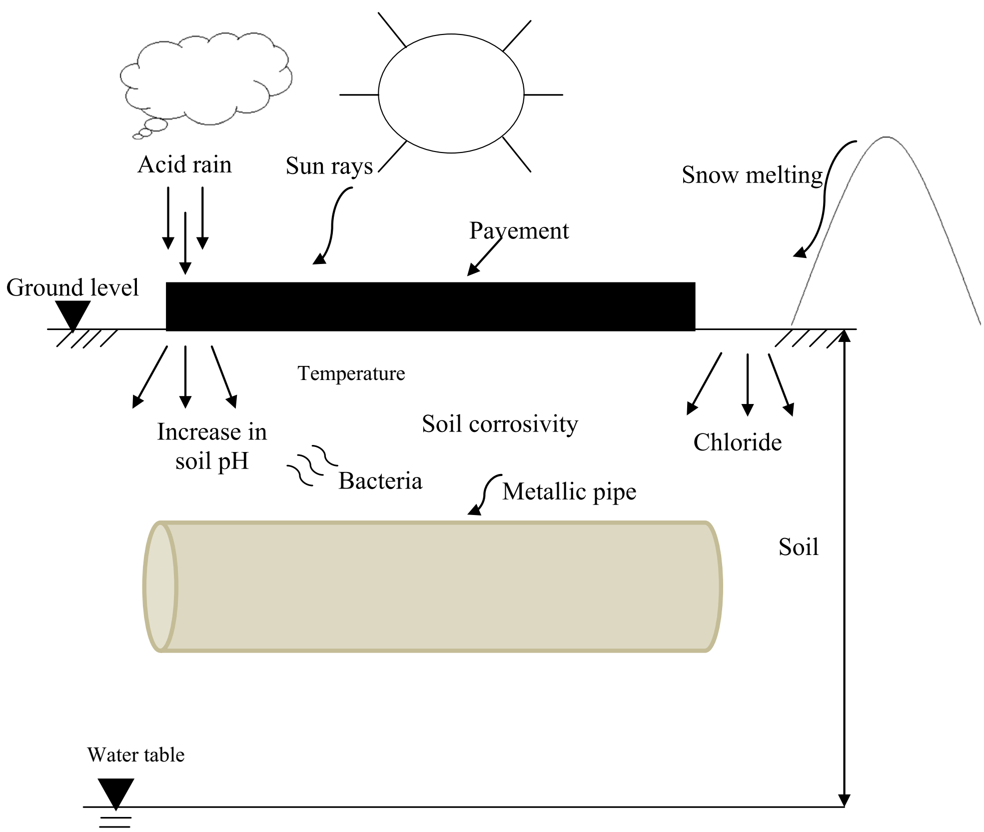


Fig. 3 Mechanism of corrosion of metallic pipe in the soil. Chloride contents are added in soil through melting of glaciers in the summer season. Chloride retards the development of stable oxide layer on the metal surface which protects corrosion. Acid rain causes an increase in pH of the soil. More acidic soil accelerates corrosion rate. Corrosion damage caused by temperature is dependent on climatic conditions. Temperature plays a vital role in regions where the yearly temperature is high

Soil properties

Background knowledge of soil and its properties and how they can influence the corrosion of buried pipes are primary steps required before carrying out research related to corrosion in the soil. It is imperative to review the physical and chemical properties of soils and their contribution to pipe corrosion. Moreover, it is important to understand how pipes were manufactured historically, as the process of manufacturing may affect the corrosion behaviour of various ferrous pipes. This section presents all of these above-said aspects.

Soils are classified according to their size range. Commonly used soils, such as clay, silt and sand, are named because of the size range of their inorganic content. Sand is classified as fine (0.02–0.2 ram) and coarse (0.20–2.00 ram). Silt particle size ranges from 0.002 to 0.02 mm, and clay particles have a diameter of <0.002 mm down to colloidal matter. The classification system is described in Table 1.

Many soil properties are governed by the particle size variation. Other terms commonly used for soil classification include clay loam, loamy sand, sandy clay, silt loam, silty clay loam, sandy loam and gravel. Clay soil is very plastic by nature; it becomes sticky and impervious when saturated with water. It has more packed particles and less pore capacity for moisture and oxygen diffusion compared with another type of soils, meaning it has poor drainage and aeration. Sand and gravel have more drainage and aeration.

In relation to the physical properties of soil, volume shrinkage is the tendency of the soil to start cracking on drying and they swell when wet. This is a property of the clay and loam particles in the soil. When clay/silt soil dries, it forms cracks that allow diffusion of oxygen to the pipe and hence the susceptibility of a buried pipe to corrosion increases. Because of the poor drainage in clay and silt, the capillary pores of these soils hold a considerable amount of water. The moisture in good conductivity soil indicates high ion content and the possibility of very active corrosion attack.

A soil's resistance (*R*) to the passage of electricity is the property of the soil that is an indicator of corrosion aggressivity. It is related to some other properties of the soil, which are given by the following term:

$$R = \frac{\rho L}{A}, \tag{1}$$

where ρ = specific gravity, L = length of the electrical path and A = cross-sectional area of the electrodes.

High compaction of the soil can change the void ratio, which in turn makes the soil more resistive. Moreover, soil with specific porosity and permeability has distinctive resistivity and the ability to corrode metal, which will be discussed in later sections.

Corrosion behaviour of buried pipes can be influenced by chemical properties of soil. The chemical elements that are responsible for causing corrosion are sodium, potassium, calcium and magnesium, and other are acid-forming elements, such as carbonates, bicarbonates, sulphates and nitrates. The conductivity of electric current (corrosion) largely depends on the soluble salts and the moisture content of the soil. pH is the measure of the soil's alkalinity or acidity, which is the logarithm of the reciprocal of hydrogen concentration. The neutrality of a soil is indicated by a pH of 7, while soil below this pH level is acidic and above it is alkaline.

Table 1 Soil classification

Soil type	USCS symbol	Grain size (mm)	
		USCS	AASHTO
Gravel	G	76.2–4.75	76.2–2
Sand	S	4.75–0.075	2–0.075
Silt	M	Fines <0.075	0.075–0.002
Clay	C		<0.002

Influence of the manufacturing method on corrosion of buried ferrous pipes

The manufacturing method of these ferrous metal pipes plays a significant role in understanding the corrosion mechanism of these pipes in soils in order to predict corrosion and to develop materials and techniques for corrosion resistance. It has been observed that pipes with different types of manufacture and metallurgical characteristics tend to fail differently due to corrosion (Trillo et al. 1995; Surnin 2008; Ralston and Birbilis 2010; Li et al. 2016). The reason for this behaviour is not well understood, but it may have a significant impact on the failure mechanism of buried pipes. This section briefly covers the pipe manufacturing processes for cast iron, ductile and steel pipes.

Cast iron

The history of cast iron manufacture is quite old, and in the sixteenth century, the first cast iron pipes were manufactured in Europe. Cast iron pipes are brittle because of their flaky graphite texture, which distinguishes these pipes from ductile and steel pipes. The typical flaky graphite texture of the cast iron pipes used in the present study is shown in Fig. 4. The shape and size of graphite are responsible for the mechanical properties of cast iron pipes, which are dependent on their manufacturing process (Makar and Rajani 2000; Bradley and Srinivasan 1990). The microstructure of cast iron pipes can be ferritic (100% iron), or it can be pearlitic, which is a combination of ferrite and iron carbide. During the manufacturing process of cast iron pipes, slow cooling results in ferrite formation with very large graphite flakes, while moderate cooling yields a pearlitic microstructure of the cast iron with fine flaky graphite. The ferritic microstructure of cast iron with fine flake graphite is promoted when rapid cooling is used during the manufacturing process (Bradley and Srinivasan 1990).

There are various types of cast iron according to its composition (Bradley and Srinivasan 1990). The carbon in cast iron ranges from 2.5 to 4.0 wt.%, the silicon content is between 1 and 3 wt.% and sulphur and phosphorus are in the

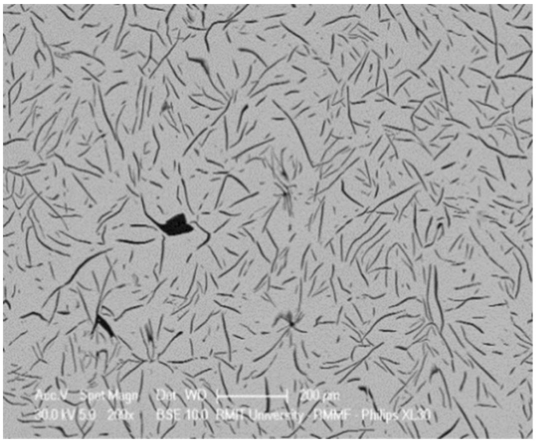


Fig. 4 Flaky graphite microstructure of cast iron pipe. Cast iron pipes have higher percentage of carbon as compared to other ferrous metals. The flaky graphite is due to the manufacturing process which makes it lower in tensile and fracture toughness properties as compared to the other ferrous metals

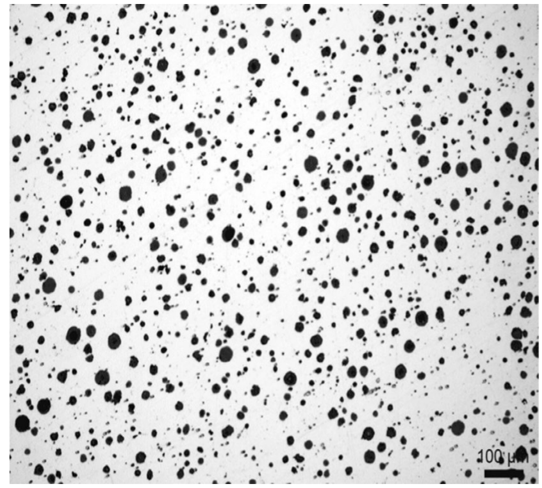


Fig. 5 Ductile iron with spheroidal graphite. The graphite content of the ductile iron is almost the same as that of cast iron. The spheroidal shape is due to the manufacturing process which makes it stronger in tensile strength and better fracture toughness as compared to the cast iron

range of 0.02–0.25 and 0.02–1.0, respectively. Manganese forms manganese sulphide in reaction with sulphur if not added during casting will result in iron sulphide formation at the grain boundaries. High levels of phosphorus also form brittle iron phosphide at the grain boundaries; its quantity is kept as low as possible to avoid the formation of iron phosphide.

Two types of cast iron, namely pit cast iron and spun cast iron, which differed because of their different manufacturing methods, were extensively used previously in various parts of the world (Makar and Rajani 2000). These two types of cast iron water pipes have distinct metallurgies. Researchers have found that spun cast iron pipes have major ferritic microstructures with small graphite flakes, while the central region of pit cast iron pipes is occupied by large graphite flakes and the outer layer is surrounded by a significant quantity of pearlite and small graphite flakes (Makar and Rajani 2000).

Ductile iron

Ductile iron is one of the types of cast iron with a different microstructure from grey cast iron. The graphite in ductile iron materials has a nodular or spheroidal shape, as shown in Fig. 5. Because of their brittleness with zero ductility, cast iron materials necessitated the development of ductile iron in the 1940s and 1950s to overcome the ductility issue. Ductile iron pipes first started to be manufactured in Australia around 1976. During the manufacture of ductile iron, magnesium is added, which allows the carbon in the metal melt to precipitate upon solidification in the form of graphite nodules within the ferritic alloy matrix. The ductility, strength and fracture toughness properties are achieved by subjecting spun cast ductile iron to heat treatment, which eliminates the brittle microconstituents produced during the casting process (Rajani and Kleiner 2003). The mechanical properties of ductile iron are better than those of cast iron pipes, and the wall thickness of ductile iron can be made much smaller than that of cast iron, according to equivalent pressure ratings. Moreover, ductile iron offers more resistance to corrosion as compared to grey cast iron.

Generally, ductile iron pipes have lower levels of sulphur and phosphorus (Bradley and Srinivasan 1990). Ductile iron pipes have better toughness than cast iron pipes, which enables them to resist cracking, and their ductility prevents sudden failure (Bradley and Srinivasan 1990). Figure 5 shows the microstructure of the ductile iron pipe.

Mild steel

Mild steel is also a ferrous metal, and it is one of the most widely used grades of steel. Its mechanical properties and composition are different from those of grey and ductile cast iron. It contains 0.05–0.25% carbon compared with other ferrous metals, which gives it superior magnetic properties and enhances its weldability. The strength of various types of steel depends on its microstructure (Krauss and Thompson 1995; Naderi et al. 2011), and all types of steel are prone to corrosion in various environments (Kuch 1988; Li et al. 2007, 2008).

Comparison of the corrosion behaviour of ferrous metal pipes

There is a difference in opinion among researchers about the corrosion behaviour of ferrous metal pipes, i.e. cast iron, ductile iron and mild steel pipes, in soils. Nevertheless, the corrosion susceptibility of cast iron in comparison with ductile iron has been well recognized by previous studies, such as Pelletier et al. (2003).

Recently, Hou et al. (2016) conducted comprehensive research on steel and cast iron specimens of the same dimensions by using simulated soil solutions of varying pH. Based on their research outcomes (Fig. 6), they found cast iron is more prone to corrosion in the same corrosive environments compared to steel. The weight loss of steel after 270 days was approximately 1000, 400 and 200 g m^{-2} in simulated soil solutions of 3.5, 5.5 and 8 pH, respectively, while in cast iron, weight loss of 1390, 420 and 390 g m^{-2} was obtained in these solutions, respectively (Fig. 6). According to this recent research, it is obvious that cast iron corrodes faster than steel.

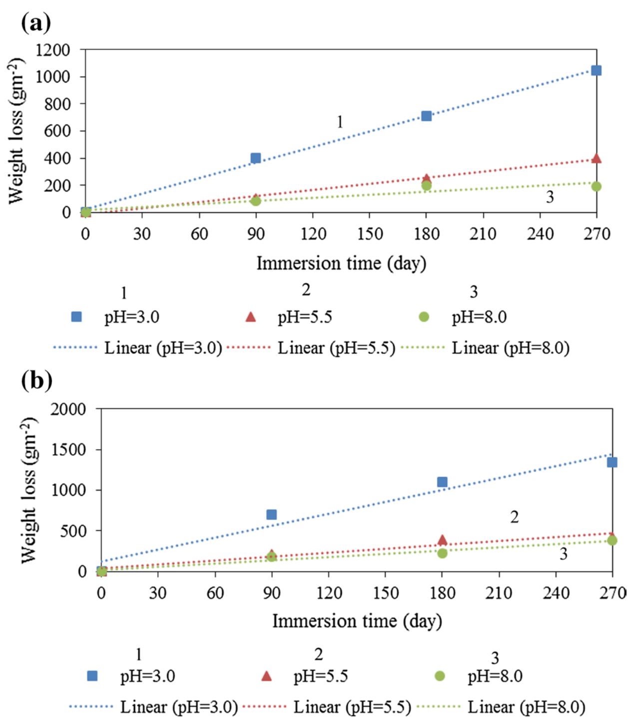


Fig. 6 Comparison of corrosion in **a** steel and **b** cast iron under the influence of different pH value and exposure duration. At pH value of 3.0, the corrosion rate of cast iron was much higher than that of cast iron showing that steel is more resistive against the high acidic medium. However, for high pH values, steel and cast iron exhibited almost similar corrosion behaviour. Redrawn by the permission of the author Hou et al. (2016)

The failure in cast iron is sudden compared with steel and ductile pipes. Steel and ductile pipe failures are in the form of leaks with no catastrophic failure. In a very recent study, Song et al. (2017) investigated the corrosion behaviour of ductile iron and carbon steel in solutions of varying chloride concentrations. They analysed the corrosion products, corrosion rates and corrosion depths of ductile and steel specimens. In their analysis of corrosion rates and corrosion depths, they found that steel specimens corroded more than ductile specimens in the same corrosive environments. A comparison of the corrosion rates of ductile and steel specimens in solutions of varying chloride concentrations is shown in Fig. 7.

On the basis of the above discussion, it can be inferred that although there is a difference of opinion among researchers about the corrosion resistance of cast iron, ductile and steel, however, a number of studies suggest that cast iron is more prone to corrosion than ductile and steel. In recent studies, ductile iron has been found to be more corrosion resistant than steel, and steel is more corrosion resistant than cast iron in the same corrosive environment.

Corrosion-induced failure of cast iron pipe

This section covers the failure analysis of buried pipes in soils, in particular of cast iron pipes, as the main focus of the present research is on cast iron. The failure modes of cast iron pipes induced by corrosion, i.e. blowout and perforation, are presented in this section.

Blowout holes

Corrosion may play a significant role in the mechanical failure of buried pipes. The combined effect of corrosion and internal water pressure can cause failure of pipes in the form of blowout holes. At first, due to the localized corrosion reaction, the pipe wall starts thinning until a point or a hole appears in it. Next, water egress occurs through this point/hole under pressure resulting in blowout failure. The size of the blowout section can be a small or large piece of cast iron, depending on the localized corrosion process and the water pressure experienced by the pipe. Figure 8 shows a blowout pipe section.

Through-wall defects/perforations

Through-wall failure (perforations) occurs when a defect caused by localized corrosion in the form of pits penetrates the whole pipe wall thickness of a pipe, so that water starts escaping. This type of defect can cause mechanical failure by inducing a failure initiation location. Moreover, due to the escape of water from the hole, the support beneath the

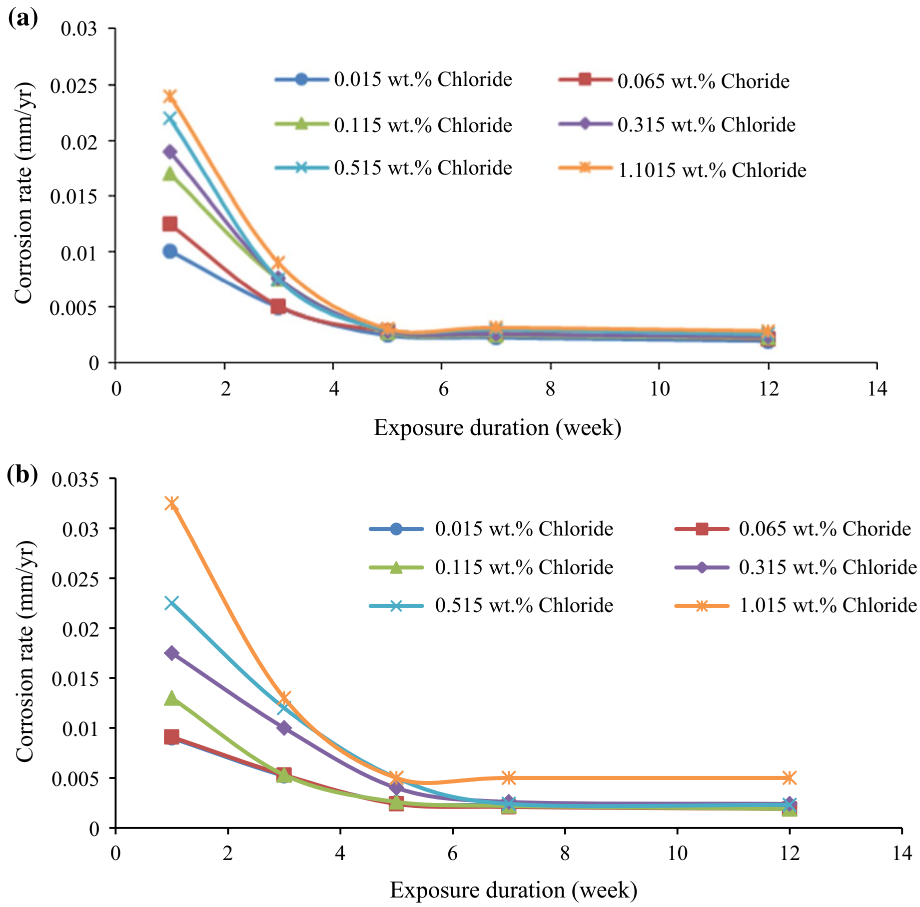


Fig. 7 Comparison of corrosion in **a** carbon steel and **b** ductile iron. Increase in chloride concentration increases corrosion rate. Initially, the effect of chloride is prominent on corrosion rate, but as exposure duration increases, there is no significant effect of chloride concentration on corrosion of carbon steel and ductile iron. However, carbon steel showed more resistance to corrosion at 1.105 wt% chloride as compared to ductile iron for an exposure duration of 1 week. Modified after Song et al. (2017)

Fig. 8 Old exhumed cast iron pipe with the blown section. This pipe section was received from City West Water, Melbourne, Australia, for the investigation of carrying out research in RMIT, University, Australia. Blowout failure is developed by internal water pressure. In this situation, pitting corrosion causes pipe to be thin until water pressure blows out remaining

pipe is washed away and the pipe starts to settle and the depth of burial increases. Figure 9 shows a photograph of a through-wall corrosion pit in a cast iron pipe. In cast iron pipes, in addition to localized corrosion, i.e. pitting, a particular form of corrosion called graphitization can also occur.

Fig. 9 Through-wall defect. This pipe section was received from City West Water, Melbourne, Australia, for the investigation of carrying out research in RMIT, University, Australia. Internal corrosion of steel pipe. The fluid flowing through pipe causes stress corrosion. As a result, thickness of pipe is reduced from that particular area and a hole is developed

Historical progress of the study of corrosion of buried pipes

This section reports on a number of studies of the corrosion of buried pipes since underground corrosion research began. The review of such studies is essential to answer questions such as how did previous researchers investigate corrosion-causing factors? What was their methodology? and how did they categorize the aggressiveness of soil factors from their research outputs? Moreover, the gaps and the limitations of previous research can be understood by reviewing previous studies. Therefore, a comprehensive review of underground corrosion was conducted and widely cited research on this topic is presented in this section.

Several researchers in the past have contributed to the field of underground corrosion of buried pipes. Whitman et al. (1925) investigated the solubility of ferrous hydroxide and its effect upon corrosion. Though this study was not directly related to underground structures, it contributed to the understanding of corrosion, which was then followed by other researchers. Schwerdtfeger (1954) measured the weight losses on cell electrodes made of steel and cast iron pipe samples after exposure to various real soils in the laboratory and compared the results with those of field investigations. He conducted experiments for 6 months on ferrous metals to study their corrosion behaviour. Based on the experimental results, Schwerdtfeger developed short-term correlations between laboratory and field corrosion measurements. Moreover, he formed the time-dependent weight loss relations and pitting corrosion relations of cast iron and steel samples in different soils. Since every research has limitations, in this research, correlation was made based on 6-month data. In addition, it is highly unlikely to be able to replicate laboratory conditions in the field.

Malvin (1958) conducted an extensive series of field tests to investigate the effect of soils on the corrosion of buried metal pipes. Romanoff considered the factors that may affect corrosion of buried pipes, such as differential aeration, moisture content, soil pores and particle size and distribution, pH, a chemical reaction between metal and soil constituents, dissimilar metals and soil shrinkage effects. He found that soil resistivity is responsible for the corrosion severity of buried pipes. Although this research is one of the most comprehensive studies related to buried pipes, it was limited to field investigations. Therefore, the time-dependent pH and aerations relations developed from this study can be questioned. Hence, there is the need for an experimental study in which many variables can be kept constant except pH and moisture, to derive time-dependent corrosion relations between pH and moisture.

Moore and Hallmark (1987) extended research related to the underground corrosion of buried pipes by conducting a field study to find the corrosivity of soils in Texas, USA. The corrosivity of soils was determined by measuring the corrosion of buried pipes at two depths for 15 different soils using electrical resistance probes. In this research, the normal standard data used at that time for characterizing soil corrosivity in the USA were found to be overestimated.

Murray and Moran (1987) monitored moisture contents to investigate corrosion behaviour of buried pipeline indoor and outdoor soil exposure. They used in situ electrochemical impedance spectroscopy measurements to understand the corrosion behaviour in different soils with varying moisture contents. In experimentation, X65 steel, polyethene-coated steel and polyethene-coated samples with defects were exposed to clay and sandy soil. The researchers found that corrosion rates were dependent on moisture content in both indoor and outdoor experiments for the bare steel and polyethene-coated steel with defects. The only limitation of this research is the control of moisture in the field, which is impossible to achieve under natural conditions.

Norin and Vinka (2003) studied the corrosion field investigation of buried metal pipes for 1 and 3 years. They differentiated uniform and local corrosion of buried metal pipes and also found the effects of the type of backfill material on the corrosion behaviour of metal pipes. The authors buried steel and zinc panels at depths of 0.5, 1.1 and 1.5 m in backfill material made up of original till-type grain distribution, wood fragments, metal pieces, bricks, seashell debris and other organic matter. Mass loss measurement, linear polarization resistance and electric resistance methods were used to determine uniform corrosion and localized corrosion with the deepest pit. An interesting observation of this research was that deep pits were found in specimens buried in the backfill material or disturbed soils compared with those buried in "natural" or undisturbed soils. The linear polarization resistance and electric resistance measurements were not found to correlate with the measured uniform corrosion rates. Moreover, the researchers did not take into account of oxygen variation that could occur at varying depths of burials.

Another study related to the corrosion of steel buried in the soil was carried out by Adeosun and Sanni (2013). In that study, the corrosion of welded mild steel bars in the soil media around the coastal area of the University of Lagos was investigated using the gravimetric method (Adeosun and Sanni 2013). For the experiments, the researchers used six (6) samples with fixed lengths and areas of 75 mm × 75 mm each for welded and un-welded mild steels. The initial weights of the specimens were recorded, and the specimens were then buried in two selected soils. The weight losses of the steel samples were determined at regular intervals for 6 months. Although this research study was of short duration and not a detailed study, it shows that even the manufacturing process of the pipes can be a cause of acceleration or resistance to corrosion in soils.

Yan et al. (2014) investigated the corrosiveness of red clay soil to metallic materials. They found that soil iron oxides (goethite, hematite, etc.) play a significant role in soil corrosion by working as cathodic depolarizers. The researchers used API X80 pipeline steel for their investigation. A set of long-term exposure tests was performed to evaluate the effect of Fe oxides on the corrosivity of the red clay soil. Steel samples 25 mm × 25 mm × 3 mm were used for the long-term exposure test. The tests were performed in a plastic container (20 cm in diameter) with outlets sealed to keep the soil water content constant at 30%, and this was checked periodically by weighing the container. Specimens were buried at 20 cm below the soil surface, and the experiments were conducted at room temperature for 60 days. EIS corrosion measurements were performed to establish the corrosivity of the red clay soil and its content. The findings of this study showed that the corrosivity of the red clay soil was reduced after iron oxides were removed from the soil. Although this study showed the importance of iron oxides in red clay soils and the researcher critical analysis, the soil was not oven-dried to kill the bacteria already present in the soil, which might have caused some variation in the results obtained.

Recently, Asadi and Melchers (2017) investigated the pitting corrosion of old cast iron pipes in the field ranging in age from 34 to 129 years and with 200–600 mm diameters. The pit depths were measured in the range of 1–2 m along the length of the pipes. The properties of the surrounding soil were also determined for correlation purposes. The pit distributions in all the pipes (ten cases) were found to differ after the comparison, and the Gumbel plot of maximum pit depth obtained from each of the cases was plotted. The investigation showed that severe pitting was at soil–pipe contact pressure points and at the locations of higher moisture in the soil.

The above studies indicate that the corrosion of buried pipes has been investigated mainly in the field where the conditions can vary at any instant of time. The control of the environmental parameters and monitoring has not been carried out. Moreover, the coupled effect of pH and acidity has not been investigated in depth in the field or under controlled laboratory conditions. Finally, long-term studies of the corrosion of cast iron in the real soil in the laboratory are very limited. In the next section, the factors in the soil causing corrosion of buried pipes are analysed in depth.

Factors influencing external corrosion in soils

Many factors in soils cause external corrosion of buried pipes. These factors have been identified by extensive field and laboratory studies (see the section Corrosion in soil). These factors include pH, moisture content, type of soil, resistivity, the presence of anaerobic bacteria, temperature, exposure duration and differential aeration. In this section, these factors are discussed in detail to find the gaps and limitations of previous studies. This will help in developing the research methodology for the present research.

pH

Correlation between pH and corrosion rates

The pH of the soil was considered as the factor most affecting underground corrosion since it was discovered. Almost all the researchers working in the field of underground corrosion relate the pH of the soil to the high corrosion rates of buried pipes. Romanoff conducted comprehensive field investigations for 25 years on the pH of soils and the corresponding corrosion of pipes between 1922 and 1957 in the USA. Thousands of specimens (29,500) were buried in numerous soil conditions, and the pH of the soil at each site was measured. The long-term mass loss of the specimens corresponding to the pH of the soils was correlated.

Penhale (1984) buried steel plates in 33 different soils for 20 years. For each soil, both the pH and total acidity were measured, and no correlation was found between total acidity and corrosion rates.

Rajani and Makar (2000) examined the corrosion rates of cast iron pipes obtained under various pH conditions of pipes, working on an American Water Works Association-funded project on the methodology for estimating remaining service life. Based on their data, again no correlation was observed between the pH and pitting rates. Doyle et al. (2003) compared the results of pH testing with the corrosion rates of samples from 98 sites in Ontario, Canada, and found no correlation ($R^2 = 0.04$) between pH and corrosion rates. The above discussion suggests that pH has little relationship with the maximum external pitting rate. The correlation between the corrosion rates of cast iron and the pH of the soils obtained from selected studies is shown in Table 2.

However, some authors from Canada still measure pH as part of their modelling of pipe failures (Rajani and Makar 2000). The American Water Works Association's rating system for soil corrosivity still lists pH as one of the criteria to be tested. This is despite the lack of any noticeable correlation between pH and corrosion in the underground environment. Based on the literature, it can be said that pH alone is a poor indicator of corrosion in buried conditions. Apart from some of the early works, no author has found a positive correlation between pH or total acidity and corrosion rate. An extremely low pH may be an indication of corrosion; however, there are many other contributing factors responsible

Table 2 Correlation between corrosion rates and pH (Dafter 2014)

Researchers	Correlation (R^2)
Penhale (1984)	Poor
Doyle et al. (2003)	0.04
Rajani and Makar (2000)	Not provided

for the corrosion of buried pipes. To conclude, there is no direct relationship between pH and corrosion rates.

Laboratories studies of pH

The corrosion assessment of deteriorated buried pipelines is difficult because of the complexity of soil structure, its resistivity and the risk of microbiologically induced corrosion. Therefore, corrosion phenomena of buried pipes are studied in artificial solutions simulating the soil to avoid complexities. For example, Belmokre et al. (1998) studied the corrosion resistance of 'primer' paint on steel exposed to conditions which simulated soil. Electrochemical impedance spectroscopy technique was used to study electrochemical behaviour of uncoated and coated plates exposed to two solutions: a reference media: 3% NaCl solution and a simulated soil solution. Experimental data were fitted using appropriate models to extract parameters of corrosion. Similarly, Benmoussa et al. (2006) used extracted soil simulated solutions (containing KCl, $NaHCO_3$, $CaCl_2$ and $MgSO_4$) along with NaCl solution to study the effect of soils on the corrosion of steel pipeline. The pH of the resulting synthetic solution was 8–8.5, and steel coupons were immersed in simulated solutions for electrochemical impedance spectroscopy studies. All of the above studies were conducted for very short durations, some for even less than a month.

Wu et al. (2010) investigated the effect of varying pH of the simulated soil (from Yingtan, China) on the corrosion of steel coupons. The pH of simulated soil was 8.1, and it was adjusted to 3.0, 4.0, 5.5 and 7.0. Q235 steel coupons were immersed in these different pH solutions for EIS studies. The researchers found that by decreasing the pH of the solution, the corrosion rates of steel coupons were increased. However, the research was conducted for less than 1 month.

Some researchers have investigated the stress corrosion cracking of pipes using simulated soil solutions. Liu et al. (2008) investigated the effect of soil pH (extracted acidic soil solution) on the corrosion of steel, specifically stress corrosion cracking. The stress corrosion cracking behaviour of X70 pipe steel was investigated using potentiodynamic polarization curve measurements, surface analysis techniques and slow strain rate testing. In another study, Liu et al. (2009a, b) investigated the effect of inclusions on the initiation of stress corrosion cracking of X70 pipeline steel in an acidic (low pH) soil solution using slow strain rate testing, scanning electron microscopy and energy-dispersive X-ray techniques. They found no initiation of stress corrosion cracking in X70 steel under anodic polarization. However, under cathodic polarization, hydrogen evolution was enhanced and caused stress corrosion cracking. Studies on the deleterious effect of hydrogen on metals/pipelines were performed in simulated soil solutions (Devanathan and Stachurski 1962; Casanova et al. 1997; Cheng 2007; Mao and Li 1998; Jin et al. 2010; Jiang and Li 2011). Some other studies on stress corrosion cracking of X52 steel (Rebak et al. 1996), API ×65 (Eslami et al. 2010, 2011) and API X70 steels in near-neutral pH and/or high pH environments have been conducted (Kentish 2007; Liu et al. 2008; Liu et al. 2009a, b; Tang and Cheng 2011; Liu et al. 2012). Recently, Yang and Cheng (2016) investigated the local corrosion at crack tips on API 5L X46 pipeline steel specimens under various loads in a simulated solution of near-neutral pH. Potentiodynamic polarization and electrochemical impedance spectroscopy combined with microelectrochemical and surface characterization techniques were employed to meet the objectives of the research.

Hou et al. (2016) recently carried out research on cast iron and steel specimens. They corroded these specimens in simulated soil solutions for three time periods: 3, 6 and 9 months, with three different pHs of 8.0, 5.5 and 3.5, respectively. The results of corrosion indicated that the steel and cast iron specimens in simulated soil solution of pH 3.5 corroded more than the other pH solutions. However, there is the possibility of a reverse trend if these experiments were conducted for longer durations, such as 1 year or more.

From the general scientific perspective, the use of simulated soil solutions to investigate the effect of pH on the corrosion of pipes is not a true representation of corrosive soil environments, because of soil's particles and physical properties. Moreover, in previous simulated soil solution studies, the maximum duration of testing was 270 days. Therefore, it is vital to investigate the effect of pH using natural soil along with a simulated soil solution in the laboratory for longer durations so that the actual effect of pH can be observed accurately and correlated with the corrosion rates.

Moisture content

The moisture content of soils plays a major role in the corrosion of buried ferrous metal pipes until a limit is reached where a decline in corrosion rates takes place. Several researchers have investigated the effect of moisture content on the corrosion of buried ferrous metals. For example, Gupta and Gupta (1979) performed a series of laboratory tests on steel specimens exposed in soils taken from three locations in India. The soil types of the three sites used in these tests were sandy, sandy loam and loamy. Mild steel test specimens 50 mm × 25 mm × 1.6 mm were burnished with emery cloth, decreased with toluene and weighed. All the three soils were oven-dried at 105 °C before the test. After 6 months, the metal coupons were taken out, cleaned and weighed for mass loss measurement. A close correlation between mass loss and moisture content exists. It is noticed by various researchers that mass loss increases with increase in moisture contents up to intermediate moisture content. They found 65% water holding the capacity to be the limit for the soils. However, it would be interesting to know how cast iron behaves with three similar levels of moisture and the extent of the corresponding corrosion.

In another study related to the corrosion of pipes in soils, Noor and Al-Moubaraki (2014) examined the effect of moisture content on the corrosion behaviour of ×60 steel in soils of different cities (Riyadh, Rabigh and Jeddah) in Saudi Arabia at ambient temperature (29 ± 1 °C). Techniques used for investigations were open circuit potential, potentiodynamic polarization and electrochemical impedance spectroscopy. The corrosion rate of X60 steel in each soil was found to increase with increasing soil moisture content up to a maximum value of 10% and then decreased with further increase in moisture content. Their study further confirms that moisture content and the corresponding corrosion of buried pipes depend on the soil's properties and its type. For any given soil, there is an optimum moisture content, which differs from soil to soil and is capable of causing high corrosion rates.

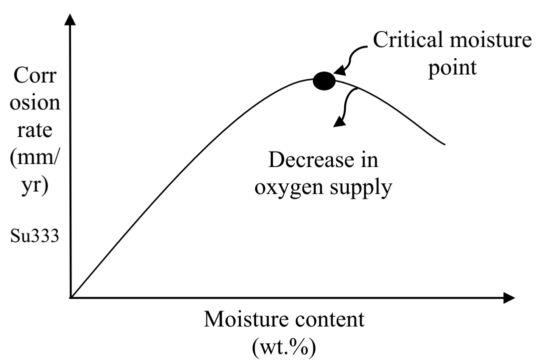


Fig. 10 Relationship between moisture content and corrosion rate for metal in soil. The corrosion rate of metal in soil increases with increase in moisture contents up to critical moisture contents. After critical moisture, corrosion rate starts decreasing. After critical moisture, the supply of oxygen to the metallic surface reduces, which causes a decrease in corrosion rate. Critical moisture is not a fixed value and dependent on soil type, metal type, exposure duration and exposure condition

From the above studies related to the moisture content and corresponding corrosion of buried pipes, it is clear that when doing laboratory experiments, it is important to select at least two extreme values of moisture content to observe the corrosion behaviour of buried pipes. For each soil, there exists a critical moisture point up to which corrosion rate of metal increases known as the critical point. Figure 10 demonstrates the existence of critical moisture point. After a critical point, a decrease in corrosion rate is observed. After a critical point, the supply of oxygen is diminished, which causes a decrease in corrosion rate. Moreover, it is also noted that most studies conducted in laboratories have been of short duration, the maximum duration being 6 months. Therefore, it is necessary to investigate the moisture effect on the corrosion of buried pipes by conducting long-term experiments lasting for 2 years, if time and resources allow. Table 3 represents effects of moisture on corrosion of metals buried in soil for different exposure duration.

Resistivity

Malvin (1958) in his comprehensive field testing developed a simple relationship between resistivity and corrosion of buried pipes. He categorized the soil's resistivity with the corrosion intensity such as the resistivity of soil over 2000 Ω-cm usually indicated the less corrosive condition. However, at a resistivity of less than 2000 Ω-cm, a high corrosion rate was expected. However, the researcher further stated that this relationship between resistivity and corrosion does not always exist and there are exceptions to it. Hamilton (1960) used data from Malvin (1958) to find the correlation between corrosion rate and resistivity. Hamilton was able to find some correlation between the corrosion rate and the resistivity of the soil below 700 Ω-cm. Contrary to Romanoff's finding that soils with resistivities above 2000 Ω-cm were non-corrosive to buried pipes, Hamilton stated that soils were corrosive below 700 Ω-cm. Hence, by using Romanoff's data, Hamilton gave the lower limit of resistivity indicative of corrosiveness of soil.

Table 3 Effects of moisture on corrosion of metal pipes

Metal	Moisture contents (wt%)	Exposure duration (months)	Soil type	Observations	References
X70 steel	20	104, 208, 416	Red soil	Pitting corrosion was noticed with increase in exposure duration	Wang et al. (2015)
X70 steel	20, 40, 60, 80	1		Corrosion rate was found increasing with increase in moisture content up to 60%	Qin et al. (2018)
Ductile iron QT400-17	20	1, 3, 5, 7, 12	Clay	At constant moisture contents, corrosion rate was noticed showing increasing trend with an increase in chloride contents	Song et al. (2017)

Further studies on resistivity and corrosiveness of soil were carried out by Booth and Tiller (1962), who was able to classify soil as aggressive or non-aggressive using 2000 Ω-cm as a benchmark or cut-off point. While continuing his investigations, Booth conducted a blind check of 28 sites for soil aggressiveness and was able to identify 21 of these sites as aggressive and six as non-aggressive, leaving one unidentified due to missing information.

Rajani and Makar (2000), working on a project with the aim of finding the remaining service life of cast iron water mains, performed a number of soil tests in the field and measured the resistivity of various soils and the corrosion rates. From the analysis of the results, it was established that lower resistivity caused more corrosion of buried pipes. However, the researchers noted some exceptions to this rule, similar to other previous researchers.

Kelly and Robinson (1993) categorized soil's corrosiveness based on its resistivity, as shown in Fig. 11. Like other researchers, Kelly and Robinson also stated that the table was arbitrary, and sound knowledge of underground corrosion was needed to assess a pipeline precisely. Moreover, Kelly and Robinson emphasized that, compared with the magnitude of resistivity at a point, the relative change in resistivity along the length of the pipe was the most influential factor in assessing pipe failure due to corrosion. This is primarily because of the creation of corrosion cells between areas of high resistivity and areas of low resistivity.

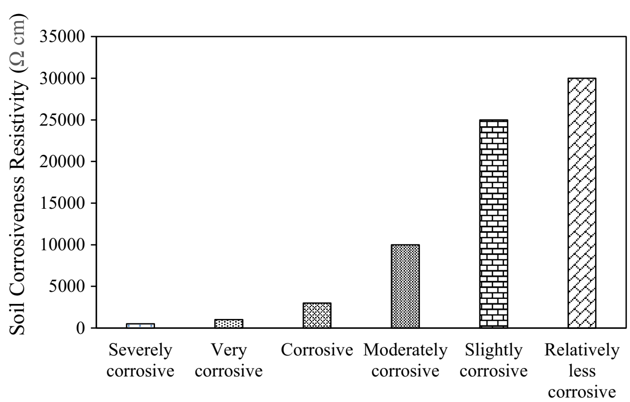


Fig. 11 Corrosiveness of soil based on soil resistivity value. There is inverse relationship between soil corrosiveness and resistivity. As soil resistivity increases, corrosiveness decreases and vice versa

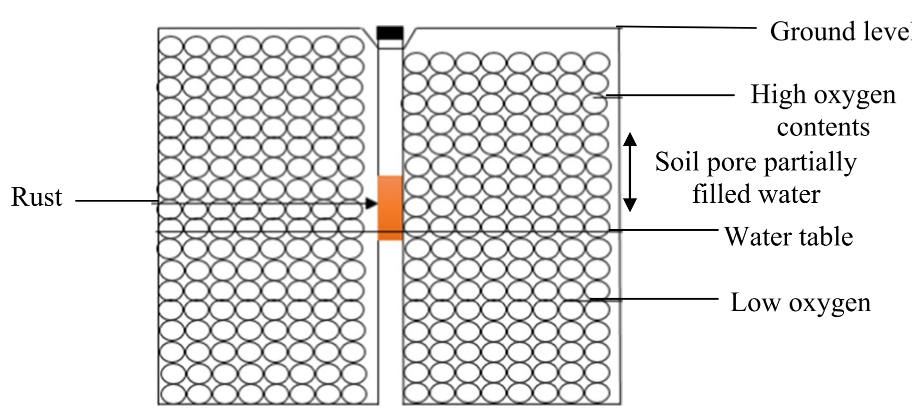
Dissolved oxygen

Research related to the dissolved oxygen concentration in soils at various depths and the corresponding corrosion of buried pipes is very limited. Neira et al. (2015) investigated the diffusion of oxygen in soil and factors involved in its diffusion; however, the effect of oxygen on corrosion of buried pipes remained unexplored. The influence of the depth and the oxygen content of the soil is explained in Fig. 12, which illustrates how oxygen concentration and the corresponding corrosion severity vary with soil depth. It can be seen from Fig. 12 that high oxygen concentration causes corrosion only when there is moisture present in the soil. This explains the corrosion process, as water and oxygen are the key factors for cathodic and anodic reactions on the metal surface. Therefore, it can be said that corrosion depends more on oxygen diffusion and the presence of water in soil pores than the depth of burial. The concept of oxygen concentration at depth and the corresponding corrosion is explained in the following sections.

If there are two different soils, one with good aeration and the other with poor aeration, differential cells are set up (Fig. 13). Soil with a low level of oxygen behaves as an anode, and soil with higher levels of dissolved oxygen behaves as a cathode. The corrosion current of the cell leaves the anode where there is a low resistivity of the soil, causing maximum pit depth. Figure 13 illustrates this phenomenon.

A differential cell is developed due to variation in oxygen concentration in various parts of the metallic pipe. Oxygen concentration cell is developed due to the differential cell, surface with an appreciable concentration of oxygen acts as cathode and surface with less concentration of oxygen acts as an anode. Factors affecting the concentration of oxygen

Fig. 12 Oxygen concentration variations with depth of soil and corresponding corrosion. Oxygen contributes to corrosion which it gets mixed with water. It is evident that metal is corroded near soil particles containing moisture as well as dissolved oxygen. However, after water table, corrosion process slows down, because less dissolved oxygen is available at this point



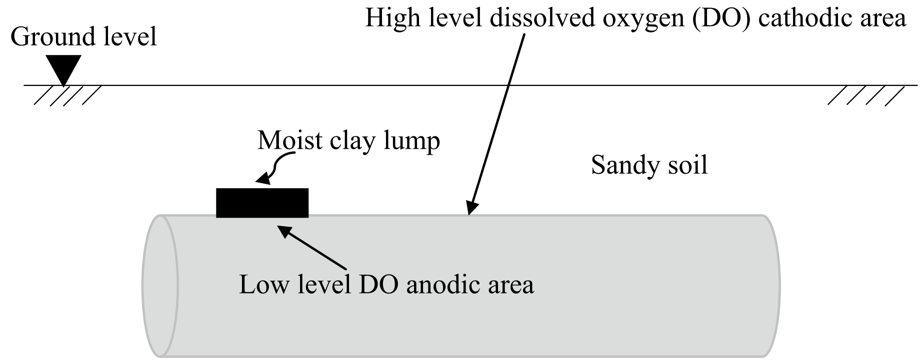


Fig. 13 Differential aeration due to two different soils. Soil containing less oxygen concentration acts as anode, and soil having appreciable concentration of oxygen behaves as cathode. The difference in oxygen concentration develops differential cell, which contributes to corrosion. Modified after Petersen and Melchers (2012)

in soil include soil type, moisture content and degree of compaction. Figure 14 below illustrates the phenomenon of differential aeration. The disturbance in the soil layout can also yield different oxygen concentration; the undisturbed soil has less oxygen than disturbed soil due to its exposure to the open environment.

In the literature survey, it was found that there has been limited research on low oxygen concentration and the corresponding corrosion of buried pipes in the open references. The reason may be the difficulty in the measurement of oxygen concentration in soils. Therefore, the effect of oxygen concentration on the corrosion of buried pipes needs to be investigated thoroughly in the laboratory.

Temperature in soil

Influence of temperature on the corrosion of reinforced concrete structures has been reported in the literature extensively. However, to date, there has been little research related to the temperature effect on the corrosion of buried metal pipes. Most studies related to the temperature effect on buried pipes highlight the inside pipe temperature, not the outside temperature of the surrounding soil, as it remains quite stable with minor variations. Seasonal variation alters the temperature of water in pipe throughout the year. Some researchers have studied the temperature dependence of corrosion of metals in aqueous solutions, including carbon steels (McNeill and Edwards 2002; Higuchi and Iida 1991; Mabuchi et al. 1991; Kritzer 2004). Some reported the corrosion of weathering steel under the influence of temperature in dry conditions (Davalos et al. 1992).

Nie et al. (2009a, b) conducted experiments on a real salty soil to determine the temperature dependence of the electrochemical corrosion characteristics of carbon steel. They selected 10% moisture content in the soil for their study. From their experimental investigation; they found that corrosion currents and passivity may be developed in carbon steel in soil at low temperatures. When the temperature increased to 50 °C in the system, the corrosion rates increased. Although the authors have contributed to temperature-related research on buried pipes, the results are not fully established, and there is a gap in understanding the temperature effect on the corrosion of buried metal pipes.

In summary, in the light of the above brief discussion, when carrying out research related to buried pipes in the laboratory, the temperature of the soil should be noted to observe any noticeable change, especially at the contact area between the soil and the pipe. Temperature sensors should be embedded at the burial depth of pipes to observe the variation in temperature at the burial depth of the specimen.

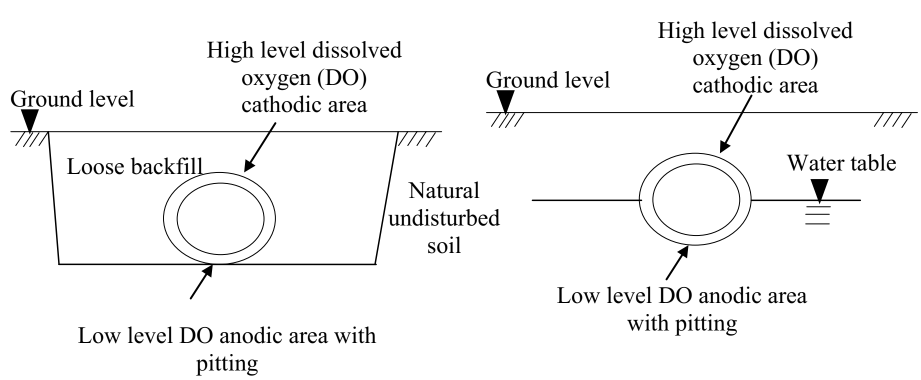


Fig. 14 Different dissolved oxygen levels. Concentration on oxygen in soil is greatly influenced by the presence of moisture. As the moisture contents increase, concentration of dissolved oxygen in soil increases. However, after critical moisture value, supply of oxygen is dimished. Modified after Petersen and Melchers (2012)

Soil particle size

Effects of soil particle size on corrosion behaviour of steel pipes are less reported in the literature. He et al. (2015) noticed that polarization resistance of ×70 follows a decreasing trend with increase in soil particle size in 3.5 wt% NaCl simulated sandy soil. Consequently, the corrosion rate of ×70 increases with a decrease in soil particle size. For soil exposure duration of 7 and 60 days, size of high-frequency semicircle decreased with decreasing the particle size ranging from 0.1–0.25 to 0.6–1.0 mm.

Exposure duration

Exposure duration is one of prime factors affecting the corrosion of metals in soil (Song et al. 2017). Metals show different corrosion behaviour depending upon exposure duration. Figure 15 demonstrates the effect of exposure duration on corrosion of X70 steel pipe in soil at different sites. It can be noticed that for short exposure duration (3 months), samples showed higher corrosion rate. As exposure duration reached 6 months, there was a decrease in corrosion rate for all sites except sites 3 and 5. The reason for the decrease in corrosion rate for long duration is the development of stable oxide layer on the metal surface, which protects the substrate from further corrosion. There was an increase in corrosion rate after exposure duration of 12 months for sites 2 and 3. The most probable reason for this behaviour can be chloride ingress, which tends to break stable oxide layer on the metal surface and accelerates corrosion rate (Song et al. 2017).

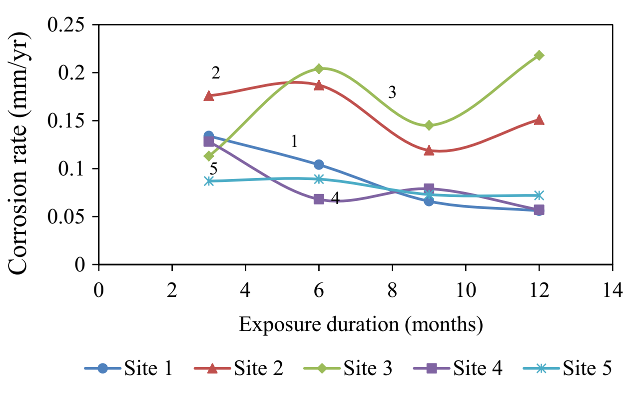


Fig. 15 Relationship between corrosion rate and exposure duration for 3 × 70 steel. Initially, corrosion rate for all sites is high except for site 3. With the increase in exposure duration, the corrosion rate is decreasing due to development of stable oxide layer. The irregularity in corrosion behaviour at sites 2 and 3 for an exposure duration of 12 months can be due to the ingress of chloride, which deteriorates stable oxide layer. Modified after Song et al. (2017)

Bacteria in soil

Microbiologically influenced corrosion is defined as the change in the corrosion behaviour of material/metal in the presence of micro-organisms (Costerton et al. 1987; Hubert et al. 2005; Hassel et al. 2012). Bacteria are attached to the metal surface and form biofilm (Dasgupta and Marrie 1987), which degrades the metal surface by changing its physical and chemical characteristics due to the biochemical activities associated with their metabolism, growth and reproduction (Hamilton 1985). Several researchers have reported microbiologically influenced corrosion as a cause of significant economic loss to the maritime, oil and gas, power generation and water distribution industries (Videla 1996; Martin 2013; El Hajj et al. 2013).

Microbiologically influenced corrosion caused by sulphate-reducing bacteria has been well reported in the literature (Booth 1964). Sulphate-reducing bacteria are anaerobic bacteria that can be found in oxygen-deficient saturated soils, with a pH from 6–8, containing sulphate ions, organic compounds and minerals, and they grow in soils at a temperature of 20–30 °C. Anaerobic bacteria have been reported to increase the corrosion process and convert non-corrosive soil to a very aggressive environment by generating hydrogen sulphide (Javaherdashti 1999). However, in well-aerated soils, the effect of anaerobic bacteria on the corrosion of buried pipes is not significant.

Many researchers have investigated the effect of sulphate-reducing bacteria on mild steel corrosion in saline environments (Bell and Lim 1981; Obuekwe et al. 1987; Beech et al. 1994; Lee et al. 1993, 1995; Melchers and Jeffrey 2008; Javaherdashti et al. 2006; Raman et al. 2005; Beese et al. 2013). Recently, Javed et al. (2015) investigated the role of ferrous ions in initial sulphate-reducing bacterial attachment and the corresponding corrosion of mild steel coupons in media with and without iron. The experiments were continued for 28 days, and the corrosion caused by sulphate-reducing bacteria in the media with and without iron was investigated and compared using weight loss measurements and microstructural studies. The results indicated that there was a small effect of the presence of iron in the culture medium and the corresponding corrosion of coupons at the beginning. However, on reaching 28 days, the corrosion of coupons in the presence of iron was very significant compared with without iron. The bacterial attachment was also investigated at various time periods during 28 days of testing. In this study, it was found that in conditions where sulphate-reducing bacteria mediate microbiologically influenced corrosion attack, the monitoring of ferrous ion levels may be more critical in practice than the enumeration of bacterial cells typically undertaken in field studies. However, the study was conducted for only 28 days, not for longer durations. Therefore, there remains a gap in understanding the exact behaviour of iron in culture media and the corresponding corrosion of sulphate-reducing bacteria.

Moreover, the research related to the corrosion of high carbon steel (such as sulphate-reducing bacteria) in soil is limited. Some researchers investigated the effect of SRB on the corrosion of carbon steel in the soil, but this study was conducted for a very short time interval of only a few days (Li et al. 2001). These researchers used electric resistance probes, polarization techniques and electrochemical impedance spectroscopy to find the effect of sulphate-reducing bacteria on metal corrosion. They concluded that corrosion rates increased 20 times those of the normal control case in soils. Although this study involved some electrochemical techniques to find the corrosion of sulphate-reducing bacteria in soils, the results are not well established as the study lasted only a few days. Therefore, there exists a gap in studies of the corrosion of high and low carbon steel caused by sulphate-reducing bacteria in soils for long durations.

Interestingly, same bacterial species are also reported for corrosion inhibition (Evans and Taylor 1972; Gaylarde 1992; Videla and Herrera 2009; Javed et al. 2014). The effect of culture medium can sometimes accelerate corrosion and sometimes provide resistance to corrosion of metals.

Although considerable research has been carried out on the influence of sulphate-reducing bacteria on corrosion of metals, the literature on the effect of sulphate-reducing bacteria on the mechanical properties of buried pipes is scant. Raman et al. (2005) investigated the effect of sulphate-reducing bacteria on hydrogen pre-charged specimens. The researchers performed slow strain rate testing of hydrogen-charged specimens in the presence of sulphate-reducing bacteria and found embrittlement, while in the absence of bacteria, hydrogen embrittlement was not observed. Table 4 demonstrates a different type of bacteria found in soil that contribute to corrosion of metals. The researchers did not investigate in depth whether the embrittlement was due to bacterial influence or some other cause. Therefore, there is gap related to the influence of bacteria on mechanical properties.

Corrosion evaluation of pipes using electrochemical techniques

This section covers the literature on corrosion measurements carried out by previous researchers on the corrosion of buried pipes. The emphasis is placed on the electrochemical measurement of corrosion of buried pipes conducted by previous researchers and the verification and correlation of these techniques by conventional mass loss measurements.

The current electrochemical techniques are of two types. One is a direct current electrochemical measurement for measuring the corrosion current (i_{corr}) at the equilibrium corrosion potential (E_{corr}). The second type is an alternating electrochemical measurement of corrosion, which uses an alternating current. The typical alternating current electrochemical technique is electrochemical impedance spectroscopy, which is commonly used for corrosion studies of metals (Dafter 2014).

Electrochemical methods were initially attempted by several researchers for the evaluation of the corrosion rates of ferrous metals in soils in the early 1950s with limited available technology and knowledge (Dafter 2014). The mass loss measurement of buried pipelines was a challenging task that gave rise to electrochemical measurements for the indirect estimation of corrosion rates without doing actual mass loss measurements of buried pipes. The application of electrochemical techniques, their shortcomings, limitations and accuracy for the evaluation of the corrosion rates of the ferrous metal pipes in soils and simulated soil are summarized in this section. The intention is to select the best techniques that can be used for corrosion monitoring and the estimation of corrosion rates in soils for the purposes of the present research.

One of the pioneering studies in the field of electrochemical measurement of buried pipe was that by Denison and Darniellec (1939). This work investigated the correlation between the mass loss of coupons measured using Faraday's law and the actual mass loss measured

Table 4 Different types of bacteria and their corrosive function

Type	Function	References
Sulphate-reducing bacteria	SRB induced cracking of a transmission oil products pipeline	Abedi et al. (2007)
Sulphate-reducing bacteria	It initiates pitting corrosion of metal in anoxic as well as oxygenated conditions	Postgate et al. (1984)
Metal-reducing bacteria	It breaks stable oxide film on the metal surface and accelerates corrosion	Lloyd et al. (2001)
Slime-producing bacteria	This type of bacteria produces extracellular polymeric substance on the metal surface	Hino et al. (1997)
Acid-producing bacteria	This type of bacteria produces organic or inorganic acid during metabolism process which makes soil more acidic and hence leading to corrosion of pipes in soil	Lu et al. (2008)

by rust removal from the coupons. Several other researchers contributed to the electrochemical measurement of underground pipes and reported good consistency between electrochemical mass loss and actual mass loss measurement in the field (Schwerdtfeger 1954; Schwerdtfeger and McDorman 1952). Serra and Mannheimer (1981) did their electrochemical measurements in the laboratory. They found polarization resistance to be the most effective measurement. The researchers carried out electrochemical measurements on steel, aluminium, copper and galvanized steel coupons in five different saturated soils, respectively, for 28 days. The difference between electrochemically evaluated weight loss and actual weight loss was approximately 20% due to packing and the varying moisture and oxygen contents of the soils. However, one of the drawbacks of the study was that the depth of burial was not considered.

Mohebbi and Li (2011) performed a comprehensive experimental investigation on the corrosion behaviour of three ex-service cast iron pipes by exposing them to three simulated service corrosive environments. Corrosion progress was measured by electrochemical impedance spectroscopy studies, such as direct current polarization and electrochemical frequency modulation after 1 year of corrosion. They examined the morphology of the corrosion products formed on the surface of the specimens using X-ray photoelectron spectroscopy. The microstructure of the specimens before and after corrosion was examined by optical microscopy and scanning electron microscope, and the researchers quantified the various phases of cast iron ex-service corroded pipe sections.

Barbalat et al. (2012) carried out corrosion studies of steel coupons buried in soil boxes mixed with deionized water and a solution of Na_2SO_4, respectively, for 2.5 months. They conducted electrochemical impedance spectroscopy, voltammetry and weight loss measurements of the steel specimens and compared the results obtained from each of these techniques. From the steel specimens under cathodic protection, a reliable estimation of an average corrosion rate value consistent with actual weight losses was determined.

In another study based on the simulated soil solutions, the long-term effect of salt concentration on the corrosion of carbon steel was determined by electrochemical measurements (Hu et al. 2013). In this study, the corrosion behaviour of rusted carbon steel in a 3% NaCl solution was studied using infrared spectroscopy for the understanding of the rust layer and the corrosion rates were measured using electrochemical impedance spectroscopy. It was found that the corrosion process is accelerated due to the presence of oxygen until the developed rust prevents its diffusion to the metal surface.

From the above discussion, it is clear that linear polarization resistance is a reliable method for the estimation of the corrosion rates of buried metal pipes. It can, therefore, be used as a corrosion monitoring tool for the current research.

Conclusion

In this paper, the fundamental knowledge and research related to underground corrosion are presented. The detailed literature review presented in this paper has shown that, despite earlier comprehensive field studies on the corrosion of buried pipes, most laboratory studies have concentrated on the moisture content of the soil and its corresponding effects. Moreover, the effect of corrosive ions and pH has been investigated using simulated soil solutions with few studies on real soils. Furthermore, studies related to the long-term effect of sulphate-reducing bacteria on the corrosion of buried metal pipes in real soils have been limited. Therefore, there is a need for laboratory studies on real soils to investigate the effect of varying pH, keeping other factors consistent. The coupled effect of moisture content, pH and the corresponding resistivity incorporating differential aeration using soil cover on the corrosion of buried ferrous metal pipes still needs to be investigated in depth, and hence there is an apparent gap related to such studies. Investigations of the long-term corrosion behaviour of buried pipes (cast iron, ductile and mild steel) in the laboratory-controlled environments are very limited. No correlation between corrosion in soil and simulated soil solutions of pipes has been developed though there are considerable studies in the literature on metal corrosion using simulated soil solution. Corrosion protective techniques such as cathodic protection are widely used for buried pipes; however, its effect on the mechanical properties of pipes is still needed to be explored. Furthermore, the effect of corrosion on the mechanical properties, such as fracture toughness of buried pipes in the soil environment, needs to be addressed in future research.

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