

LONG-TERM CORROSION OF CAST IRON CEMENT LINED PIPES

R.B. Petersen, R.E. Melchers

Centre for Infrastructure Performance and Reliability, The University of Newcastle, Australia

SUMMARY: The corrosion of ferrous water mains is a significant problem for the Australian Water Industry. A significant proportion of Australia's ageing water infrastructure is composed of cast iron and steel cement lined pipes, which are prone to corrosion on the external surfaces that are in contact with soil. Internal corrosion is not a significant issue for cement-lined pipes. For the water industry to manage these ageing assets effectively, quantitative predictions of the damage likely to result from long-term corrosion are highly desirable. Many of the fundamental corrosion mechanisms are known and there is considerable practical experience on the corrosion of buried iron. However, the prediction of the long-term corrosion losses, of pit depths and pitting extent are not well developed, including understanding and prediction of the quantitative influences of external soil conditions. In this paper the basic mechanisms involved in the corrosion of ferrous metals in contact with soil are reviewed and the likely effects of various influencing factors such as soil moisture content, soil type and soil water chemistry on long-term corrosion are described. The review has found that long-term corrosion is controlled by diffusion processes and is a function of soil moisture content, soil density, and soil water quality. The review is followed by an outline of an approach to modelling long-term corrosion of cast iron pipes. It involves developing a realistic model for the prediction of pipe corrosion in soil and its calibration to field and historical data. Both the modelling approach and field data collection requirements are outlined.

Keywords: Cast iron, Water pipe, Soil, Long-term, External corrosion, Model.

1. INTRODUCTION

Australia's urban water distribution systems are ageing and are becoming more prone to failure. Worldwide about 70% of the total asset base of a typical urban water utility consists of buried pipes in congested cities. In many cases large portions are old, some over 100 years. With further ageing of this vital infrastructure, supply main failures will continue to increase (Nicholas and Moore 2009). Large diameter pipes within the network are especially critical since there is little or no redundancy and there are high consequences of failure. Being able to predict the remaining service life of critical pipes would allow utility owners to better manage these ageing assets. To predict remaining service life, knowledge is required of the current condition of a pipe, the rate of deterioration, the loads acting on the pipe and the load-structural response of the pipe. An industry funded, collaborative 5 year research project involving Monash University, the University of Technology Sydney and The University of Newcastle commenced in 2011, to gain information and develop models to assist in predicting the remaining service life of critical pipes. The long-term rate and extent of pipe corrosion are being investigated by The University of Newcastle, and are the focus of this paper.

One type of pipe being investigated is cast iron cement lined (CICL) pipe. A significant proportion of Australia's ageing water infrastructure is composed of these pipes. Deterioration of CICL pipes used in Australian conditions is predominantly corrosion on the external surfaces that are in contact with soil. Experience shows that corrosion will consist of cast iron thinning, graphitisation (leaching out of iron components), and pitting. Internal corrosion of CICL pipes is not a significant issue as the cement liner has a much longer life than the cast iron under normal conditions (Nicholas and Moore 2009).

To predict the remaining service life of these pipes a realistic predictive model of corrosion versus exposure time (as a function of external soil factors) is required. To date, it appears that such a model does not exist, although several quasi-empirical and empirical models have been proposed (Romanoff 1957, Rossum 1969, Rajani et al. 2000, Caley et al. 2009,

among others). These are discussed in a recent literature review (Cole and Marney 2012). Most of the current models are essentially based on curve-fitting techniques, with little or no input of corrosion processes. Only the model proposed by Rossum (1969) makes some attempt to take into account corrosion processes. It does not, however, model the physical processes directly (such as the diffusion of reactants and products through corrosion rust layers), but relies on geometric and proportionality arguments (cf. Cole and Marney 2012). Another issue with current models is that they are all based on a power law or an exponential function (or similar), and therefore assume that corrosion levels off against time. Based on many empirical observations of iron corrosion in several different 'wet' corrosion environments, this assumption may not truly represent the time-dependent corrosion behaviour for all cases (Melchers 2011). Rather, it has been observed that 'wet' corrosion of iron typically follows a bi-modal trend with time, as will be discussed later in this paper.

A more realistic predictive model for corrosion (thickness loss and pit depth) versus time should be based on fundamental corrosion science and physics. The model also should account for the effects of external soil conditions. The model will be an improvement over existing models because it will be based on the actual rate controlling processes. With the view to developing such a more realistic model, in the following paper a review is given of cast iron corrosion, the processes occurring during cast iron corrosion in soil and the external soil factors that influence the corrosion process. This is followed by an outline of the proposed approach to modelling long-term corrosion of cast iron pipes. An outline is given also of the field data collection requirements for calibration of the model.

2. CORROSION OF CAST IRON PIPES

Up until 1975 grey cast iron was used as the form of cast iron for pipe manufacture in Australia. Thereafter, grey cast iron was replaced with ductile cast iron (Nicholas and Moore 2009). The majority of old cast iron pipes at risk of failure from corrosion are therefore of the grey variety and are considered in this paper. Further reference to cast iron in this paper will mean grey cast iron. The corrosion of ductile cast iron will not be discussed in this paper. Grey cast iron is an iron alloy consisting predominantly of iron with 2.5-4 % carbon, 1-3 % silicon and minimal other alloys. The carbon is mainly in the form of graphite flakes, which are arranged in an almost continuous network. This network of graphite flakes gives the grey cast iron its brittle properties, and grey colour upon fracture.

The corrosion of cast iron involves thinning, pitting, and graphitic corrosion (Makar et al 2001). Cast iron thinning and pitting occurs in much the same way as in steel, with metal lost to the solution. Graphitic corrosion is unique to cast iron and involves the selective leaching of iron components from the iron-graphite matrix of which cast iron is composed. A matrix of graphite flakes is left, and has a significantly lower structural strength than the original metal. Typically the matrix of graphite flakes is held together by the iron oxide corrosion products, and it may retain the un-corroded shape of the original metal. This graphite-iron oxide structure is commonly referred to as the 'graphitised zone'. Figure 1 shows an example of a corroded cast iron pipe section, with the graphitised zone removed by abrasive blasting.



Figure 1 Exterior corrosion of a 110 year old cast iron water main with graphitised zone removed

3. LONG-TERM CORROSION OF CAST IRON

The corrosion of ferrous metals in contact with aerated water typically follows a monotonic bi-modal trend with time (shown schematically in Figure 2). This trend has been observed for various metals (mild, low alloy and weathering steels) in various environments (seawater and freshwater immersion, tidal zone, coastal and inland atmospheric exposures) (Melchers 2011). Trends from Romanoff's (1957) data for corrosion mass loss of ferrous metals (both steels and CI) in soils show similar trends (Figure 3). Mass loss and pit depth data for CI in immersion conditions also follow a bi-modal trend, when carefully interpreted (Melchers 2012).

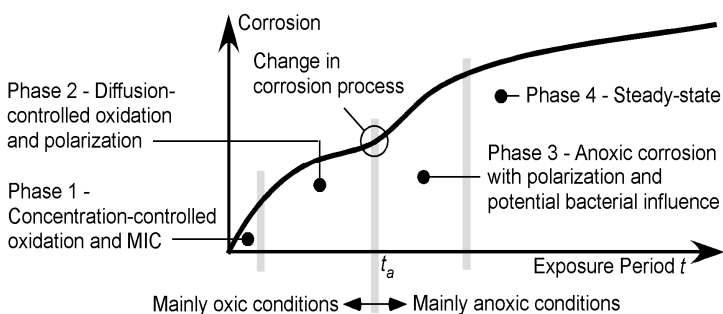


Figure 2 Schematic representation of the bi-modal behaviour of corrosion loss showing principal phases

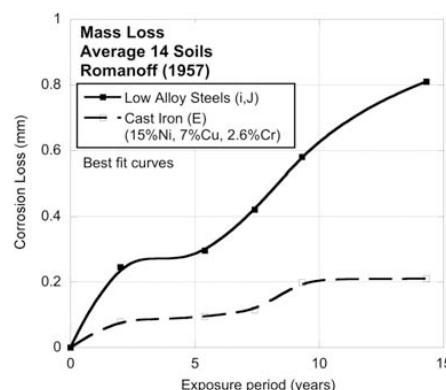
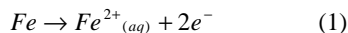


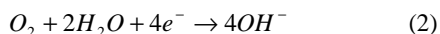
Figure 3 Trends for average corrosion mass loss of pipe coupons buried in soils for two low alloy steels (I, J) and a high alloyed cast iron (E). Data from Romanoff (1957), T29.

The phases of the bi-modal function are now described for the case of cast iron corroding in the presence of aerated water. This scenario is likely to be that observed in unsaturated soils, above the water table. Phase 4, representing the long-term behaviour, is considered in greatest detail. Potential bacterial influence (as identified in Figure 2) is discussed in a later section.

In a moist soil environment, the corrosion of cast iron is essentially wet corrosion of the iron component. At anodic sites on the metal, ferrous ions are dissolved into the electrolyte solution:



The electrons released at the anodic sites are accepted at separate, cathodic sites. The cathodic reaction is:



The ferrous and hydroxide ion react to form the various iron oxide corrosion products. Depending on their solubilities, these rust products are deposited within the graphitised zone, on the external surface of the pipe, or diffuse away into the surrounding soil.

During phase 1, the rate of corrosion is controlled by the rate of diffusion of oxygen to the surface of the metal from the surrounding environment. For cast iron buried in a soil, this rate is dependant on the permeability of the soil adjacent to the pipe, the moisture content and the depth of burial.

In Phase 2, the rate of corrosion declines. This decline is due to a build up of rust products on the external surfaces and an increasing depth of graphitised zone. The rust products provide an obstruction to the inward diffusion of oxygen to the surface of the metal, which reduces the rate of corrosion.

In Phase 3, the rate of corrosion increases initially, but then gradually declines in time. This increase in corrosion rate has been attributed to a change in the corrosion process from one involving oxygen reduction (controlled by oxygen diffusion), to one involving hydrogen reduction (controlled by hydrogen diffusion) (Melchers 2011). Hydrogen reduction is thought to occur in crevice-type formations on the corroding surface. These crevices develop at anoxic (oxygen-restricted) niches on the corroding surface, due to non-uniform oxygen access. This behaviour has been described for steel, and may occur during the corrosion of CI. The mechanisms involved at the end of phase 2 and the start of phase 3 (surrounding the changeover) are currently under investigation. It is thought that the corrosion rate is controlled by diffusion across a thin layer of magnetite (iron oxide rust product) at the surface of the metal.

By Phase 4, steady-state conditions are established. This phase is the most important for the prediction of the long-term corrosion rate of CI in soil. For buried pipes, Phase 4 may be entered as late as 10 -20 years after initiation (Figure 3). All of the pipes undergoing condition assessment in this project will be older than this period, and therefore will lie in Phase 4. The basic processes involved in the long-term are now discussed in greater detail for the case of cast iron in contact with moist soil.

Figure 4 shows an idealisation of the corrosion process in the long-term (Phase 4). The corroding surface has retreated into the cast iron component leaving behind a graphitised zone. Rust products have built up on the external surface of the metal in contact with the external environment, and also within the graphitised zone. On the corroding surface a crevice-type formation has developed due to non-uniform oxygen access to the corroding surface (developed during Phase 3). Figure 4

illustrates a case where the graphitised zone has retained the original shape of the pipe, and there has been no observable thinning or pitting (non-graphitic corrosion) of the pipe material.

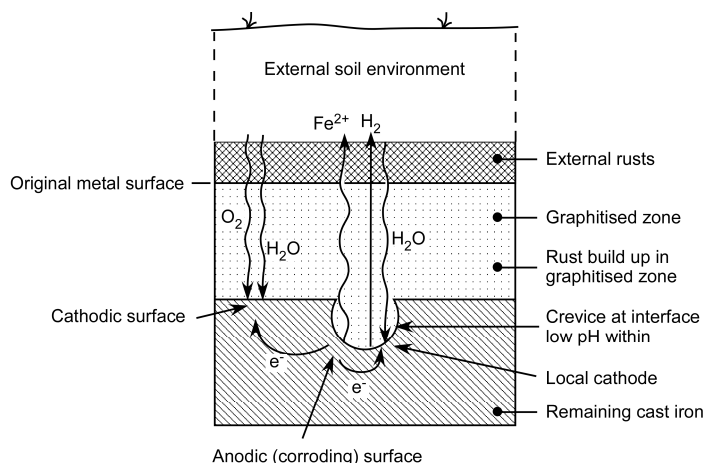
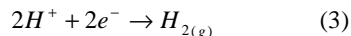


Figure 4 Schematic view of the diffusion processes active during the corrosion of cast iron in reasonably moist, neutral, and aerated soil (phase 4).

Two corrosion processes may be active, the first being oxygen reduction outside of the crevice (Eqn 2), with corresponding anodic process within the crevice (Eqn 1). This separation of cathode and anode is a result of differential aeration between the inside and outside of the crevice, thus creating a differential aeration cell. Possible rate limiting processes include the inward diffusion of oxygen and water to the cathode, and the outward diffusion of ferrous ions away from the anode. Oxygen and water must be replenished at the corroding surface, and ferrous ions need to be removed from the corroding surface to sustain the corrosion reactions.

The second corrosion process involves hydrogen reduction at the cathode within the crevice (Eqn 3), with the corresponding anodic process within the crevice also (Eqn 1). The cathodic reaction within the crevice is:



This reaction involves the evolution of hydrogen gas, and is typically much slower than (Eqn 2), except when in acidic conditions ($pH < 4$) (Uhlig 1963). Conditions within the crevice are acidic allowing the reaction to proceed quickly. Possible rate limiting processes include the inward diffusion of water to the cathode (in the crevice), the outward diffusion of hydrogen gas from the cathode, and the outward diffusion of ferrous ions away from the anode.

The slowest diffusion process will control the corrosion rate. The outward diffusion of ferrous ions is likely to govern since its atomic size is much larger than that of the other diffusing species, as first proposed by LaQue in 1958. Note that since the outward diffusion of ferrous ions is likely to govern the reaction rates, both of the cathodic processes described may be acting simultaneously. The rate of diffusion of ferrous ions will be affected by the permeability and thickness of the graphitised zone and external rusts. The rate of diffusion will also be affected by the level of saturation of these layers.

Under saturated soil conditions (under the water table), oxygen is typically absent (Jack et al. 1995, Schlesinger 1997). Under these conditions the main cathodic reaction is hydrogen reduction (Eqn 3), following the dissociation of water. As noted before, this reaction rate is typically much slower than (Eqn 2), leading to a much reduced initial corrosion rate compared to that in aerated water. Over time the corrosion rate will fall as the graphitised zone increases in thickness and rust products develop within the graphitised zone and on the external metal surface. Diffusing species include water and ferrous ions. It is likely that the outward diffusion of ferrous ions will control the corrosion rate in the long-term. In this case the bi-modal behaviour (with an increase in corrosion rate after a significant exposure time) is not expected, but rather a trend closely approximated by a power law would be observed.

4. FACTORS THAT AFFECT THE CORROSION OF IRON IN SOIL

From the literature the external soil factors that influence the corrosion of iron in soil include: soil type, moisture content, the degree of aeration, resistivity, pore water chemistry, microbiological activity, and temperature. These factors, and their likely effects on long-term corrosion losses and long-term corrosion rate, are now discussed.

4.1 Soil type

The corrosiveness of a soil towards metal is affected (to varying degrees) by the soil's physical properties, mineralogy and organic content (Jack and Wilmott 2011). In engineering, soils are defined by these factors and are broadly classified into the following groups: (1) coarse-grained soils (sands and gravels), (2) fine-grained soils (silts and clays), and (3) highly organic soils (peats) (ASTM 2011).

The soil physical properties that have the strongest effect on corrosion are those that define the soil permeability and water-holding capacity, such as particle size, particle distribution and overall soil structure. The soil permeability controls the rate of movement of water and air in the soil, and so can affect: the soil moisture content next to the pipe and its variation with time, and the degree of aeration. As an example, coarse-grained soils have a high permeability and low water-holding capacity, and typically have good drainage and good aeration. Fine-grained soils such as clays, on the other hand, have a low permeability and high water-holding capacity, and typically have poor drainage and poor aeration. The effects of moisture content and degree of aeration on the corrosion rate are discussed in more detail in the following sections.

Soil mineralogy affects groundwater chemistry, which is discussed later. Decaying organic matter in soil supports biological activity, which may influence corrosion losses and rate. The influence of biological activity is also discussed later.

4.2 Moisture content

Water is the essential electrolyte required to support the electrochemical corrosion process (Roberge 2008). It is expected then, that the amount of water in the soil and (more importantly) in contact with the metal surface is a significant influencing factor for the corrosion of iron in soil. Practical observations and scientific investigations support this statement. Practical experience has shown that the corrosion of iron in a dry soil is much less than the corrosion of iron in a moist soil (Roberge 2008). In a recent review of the scientific and engineering literature on iron corrosion in soils, Cole and Marney (2012) concluded that the only factor that is consistently found to control corrosion (rate and extent) is the soil moisture content.

Water in a soil is either adsorbed on the soil particles ('hygroscopic water'), is held tightly in capillary pores ('capillary water'), or exists in larger pores which are too large to hold onto the water by capillary action (known as 'free' or 'gravitational' water). The moisture content of a soil is the sum total of all the water contained in the soil.

The effect of soil moisture content on short-term corrosion rates (six months) has been studied and discussed by Tomashov (1966) and Gupta and Gupta (1979). In the short term, it has been shown that corrosion mass loss of iron in soil changes with moisture content. At low moisture content, protective rust layers form quickly, close to the metal surface and the corrosion rate is controlled by the anodic process. As the water content increases the corrosion rate also increases, up to a maximum value. Afterwards the corrosion rate decreases with increasing moisture content. At high moisture contents, more of the soil pore spaces are filled with water (in place of air); slowing down the rate that oxygen can diffuse to the metal surface. The corrosion rate is then controlled by the rate of diffusion of oxygen through the pore water. The more water filling the pore spaces, the slower the short-term corrosion rate. Gupta and Gupta (1979) found that the maximum corrosion mass loss in soil occurs between 25-35 % moisture content by weight. This was determined for mild steel specimens in three different soils, exposed for six months.

In the long-term, the corrosion rate of CI is likely to be controlled by the diffusion of ferrous ions away from the corroding surface (as discussed previously). This diffusion rate is affected by the permeability of the graphitised layer (with embedded rusts) and the external rust layer. The diffusion rate of the ferrous ions would also be influenced by the porosity and level of saturation of these layers. The moisture content of the soil surrounding the metal will have an effect on the development of rusts within the graphitised zone and external layer. The soil moisture content will also have an effect on the saturation level of the rust/graphitised-zone layers. Therefore, it is considered that the long-term corrosion rate will be strongly influenced by the surrounding soil moisture content level in the vicinity of the anodic region. At a low moisture content level (lower than say 25 % by weight), observations have shown that more adherent rusts develop more quickly, resulting in a lower permeability of rust (and graphitised zone) layers and lower corrosion rate (Tomashov 1966, Gupta and Gupta 1979). At high moisture content levels (higher than say 25 % by weight), rust products tend to diffuse out into the external soil environment more easily, resulting in a higher permeability of rust (and graphitised zone) layers and higher corrosion rate in the long term (Romanoff 1957, Uhlig 1963).

4.3 Degree of aeration

Degree of aeration refers to the ease of access (or transport) of oxygen in a soil, and is related to the soil physical properties and moisture content. Another related parameter is the oxidation-reduction potential of the soil, which is a qualitative measure of the oxygen level at a particular level in a soil (Roberge 2008, Jack and Wilmott 2011).

The degree of aeration reduces with increased moisture content (air and water compete for space in the soil pore spaces). The degree of aeration also reduces with soil compaction and therefore burial depth (underlying soil is compacted by overlying soil layers). Also, oxygen levels typically decrease with burial depth, due to consumption from organic processes in the soil (Kreysa G and Schütze, 2008).

The affects of aeration on the corrosion rate are strongly interrelated with the affects of moisture content. At low moisture content, the degree of aeration (and potentially the level of oxygen) is relatively high. The available oxygen oxidises corrosion products into less soluble more adherent products. In the long-term the corrosion rate would be likely low. Alternatively, at high moisture content the degree of aeration is low. In the long-term the corrosion rate would likely be higher (than the low moisture content/ high aeration case), as discussed in the previous section.

An extreme case of the effect of soil compaction on corrosion can be observed for driven vertical steel piles. During installation the soil adjacent to the pile becomes heavily compacted. As a result of this compaction the permeability of soil adjacent to the pile is reduced and the access of oxygen (and water) to the steel surface is restricted. The corrosion in this case is then much less than corrosion observed in laid pipes (Romanoff 1962, Ohsaki 1982).

4.4 Differential aeration

Variations in oxygen access to different regions of a metal pipe surface may result in the formation of a differential aeration cell across a relatively large distance. Differential aeration creates an oxygen concentration cell, where the surfaces with access to the greatest amount of oxygen become cathodic and the surfaces with restricted oxygen access become anodic (with associated metal loss). Variations in oxygen access in a soil may be a result of variations in soil type, moisture content, and degree of compaction.

Three typical cases of pipeline corrosion due to differential aeration are shown in Figures 5-7. Note that the typical depth of a buried pipe is 800 mm below the surface of the ground, but may be deeper in some circumstances. These corrosion cases have been observed in practice. Figure 5 illustrates a common case where there is a difference in aeration between the top and the bottom of a pipe. This scenario may develop if the bottom of the pipe is laid on undisturbed soil at the bottom of an excavated ditch and a more permeable material (sand backfill) is placed around the pipe (Roberge 2008). A similar differential aeration cell, shown in Figure 6, may develop in pipelines where the water table is at or near the bottom of a pipe (Romanoff 1957). The bottom surface of the pipe becomes anodic and hence is more severely corroded in both cases. Figure 7 illustrates another common case where severe corrosion is observed under a large piece of clay stuck to the surface of the pipe. The other surfaces of the pipe are in contact with more permeable soil and are better aerated. A photograph showing corrosion damage of this type is shown in Figure 8.

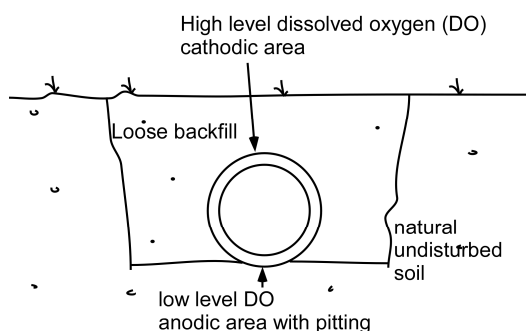


Figure 5 Differential aeration cell formed by laying a pipe in a ditch and surrounding it with loose backfill

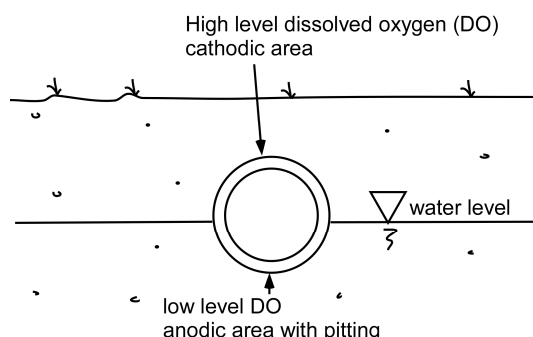


Figure 6 Differential aeration cell occurring in pipe at water table level

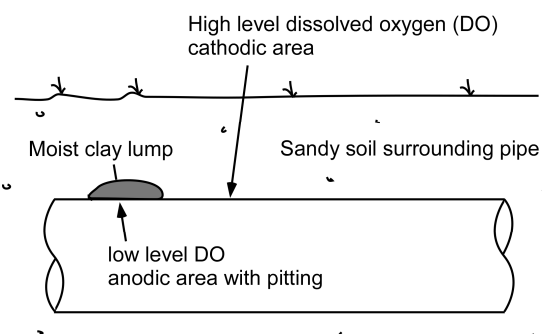


Figure 7 Corrosion caused by different soils in contact with pipe



Figure 8 Photograph of corrosion by different soils in contact with pipe. Note that the corroded area is located on the bottom of the pipe when the pipe was in service.

The resistivity of the soil electrolyte is an important factor in the establishment of a differential aeration cell. The resistivity of the soil electrolyte is discussed in the next section.

4.5 Resistivity

The electrolytes dissolved in the soil water carries the corrosion current between the anode and the cathode to complete the circuit required for corrosion to occur. The electric current is carried by ions in the electrolyte in the water. Soil resistivity is a measure of how strongly the soil opposes the flow of an electric current, and is the inverse of conductivity. Soil resistivity is influenced by a variety of factors including: solution ionic content, moisture content, soil type, degree of compaction, and temperature (Doyle et al. 2003, Roberge 2008, National Highway Institute 2009). Low values of soil resistivity are associated with: high solution ionic content, high moisture content, fine soil texture, low degree of compaction, and high temperature. Resistivity is typically measured in a laboratory on remoulded and saturated specimens (National Highway Institute 2009).

In general, it is believed that as soil resistivity decreases, the corrosion rate of buried iron or steel increases. Soils with resistivity values less than 2000 ohm-cm are generally considered corrosive (Jack and Wilmott 2011, National Highway Institute 2009, Doyle et al 2003). Several researchers have attempted to correlate soil resistivity with corrosion (Gummow and Wakelin 1993, Jakobs and Hewes 1987, O'Day 1989, Doyle et al 2003). In general, only weak correlations between soil resistivity and corrosion have been observed (Cole and Marney 2012).

Soil resistivity may affect only specific types of corrosion cells active on a buried structure. Tomashov (1966) suggests that corrosion in a soil can be divided into two different forms: a micro corrosion cell leading to general corrosion and a macro corrosion cell leading to localised corrosion. Micro corrosion cells form as a result of non-homogeneity in the composition of the metal structure. These cells are established over a short distance (of the order of a mm or less), with the anode and cathode located relatively close to one another (leading to general corrosion). A change in bulk soil resistivity has little effect on the rate of this type of corrosion. Macro corrosion cells form as the result of variations in the structural and chemical properties of the soil (and soil water) surrounding the metal. These cells are established over a long distance (of the order of metres), separating anode and cathode, and leading to localised corrosion. Low resistivity is considered to lead to acceleration of this type of corrosion (Tomashov 1966, Jack and Wilmott 2011, National Highway Institute 2009). A typical form of macro corrosion cell is the differential aeration cell, which was discussed in the previous section.

In the short-term a low soil resistivity may facilitate the establishment of differential aeration cells. This would allow soil regions in contact with the pipe with low dissolved oxygen (such as saturated regions) to tap into an oxygen supply in soil regions in contact with another section of the pipe. Separation of anode and cathode (as a result of the differential aeration cell) may result in a spread of corrosion products, reducing the level of coverage provided by them (Romanoff 1957). In the long-term, once corrosion products build-up to a significant amount, the differential aeration cell is likely to be disconnected, due to a high local resistance of current flow across the rust barrier. Instead only local micro-galvanic corrosion cells would be active.

Apart from a possible spreading of corrosion products in the short term, resistivity of the bulk soil should not have a direct influence on the long-term corrosion rate. That is, bulk soil resistivity should not have a direct effect on the rate of species diffusion through the graphitised zone and rust layers. Soil resistivity is therefore unlikely to directly influence the long-term corrosion rate. Rather, the underlying factors that influence soil resistivity (such as moisture content, degree of aeration, water chemistry) are likely to have a more direct influence on the long-term corrosion rate.

4.6 Microbiologically influenced corrosion

The activity of micro-organisms (such as bacteria) in the soil may influence the rate and extent of corrosion. Several forms of bacteria have been implicated in the corrosion of ferrous metals, with the most attention given to sulphate-reducing bacteria (SRB) (Roberge 2008).

There are many reports of accelerated corrosion in saturated soils in the presence of SRB (von Wolzogen and van der Vlugt 1934, Jack and Wilmott 2011, among others). The sulphate-reducing bacteria are only active in oxygen-free environments, such as in saturated soils and potentially within anoxic (oxygen-free) niches developed within rust layers. These organisms take nutrients and sulphates (SO_4^{2-}) from the external environment and produce hydrogen sulphide (H_2S) as a waste product (Schulze and Mooney 1993). This waste product then reacts with (corrodes) the iron to form iron (II) sulphide (FeS) (Crolet 1992).

The nutrients used by the SRB include simple organic acids and molecular hydrogen (H_2) from decomposing natural organic matter. Saturated soils with high levels of organic matter and high levels of sulphates are typically considered aggressive to metals, due to the activity of SRB (Roberge 2008, National Highway Institute 2009).

In the short term, SRB colonies reside in a bio-film on the surface of the metal. In a saturated soil, the short-term rate of corrosion would be proportional to the amount of available nutrients. As corrosion occurs and the rust layer (and graphitised zone layer) builds up, SRB colonies may also come to reside within these layers (Melchers 2009). Potential rate limiting

processes involved in the corrosion of iron by SRB-produced- H_2S include: the diffusion of nutrients and sulphates to the SRB colonies from the external environment, and the diffusion of waste products (H_2S) from the SRB colonies to the metal surface. The diffusion of water in and ferrous ions out are other possible rate limiting processes. In the case of saturated soil conditions, it is likely that the diffusion rate of nutrients and sulphate ions in from the external environment would be extremely slow. However, the diffusion of water in would be significantly quicker. The main cathodic reaction would then be hydrogen reduction following water dissociation (Equation 3) as in the case where no bacterial activity is present. Thus, (as was the case for saturated soil) it is likely that the outward diffusion of ferrous ions through the rust and graphitized zone layers will control the corrosion rate in the long-term.

4.7 Soil water chemistry

The pH of common soils typically varies between 5 and 8. In this range, pH has little direct effect on the corrosion rate, when compared with other factors (Roberge 2008). It is expected that most of the pipes studied for condition assessment in this project will be buried in soils with pH levels within this range. However, some highly acidic or highly alkaline soils may be encountered. Acidic soils (pH of 3-6) occur in such natural environments as swamps or those containing a large amount of organic matter (humus soils) (Tomashov 1966). The corrosion of iron as a function of pH increases considerably at pH values less than 4 (Uhlig 1963, Jack and Wilmott 2011). Under such conditions, the solubility of corrosion products increases and protective corrosion product layers are difficult to form. Both cathodic reactions (Equations 2 and 3) occur simultaneously, uninhibited by corrosion product build-up, resulting in very appreciable corrosion rates (Uhlig 1963).

The pH of alkaline soils (7.5-9.5) is unlikely to have a direct influence on corrosion rates. Some forms of alkaline soils (calcareous soils) contain high levels of calcium and magnesium ions in the pore water, which have the potential to form protective carbonate deposits over cathodic surfaces (Roberge 2008, Jack and Wilmott 2011). The carbonate layer would likely add to the protective iron oxide rusts formed by the corrosion process and reduce the long-term corrosion rate. High levels of calcium and magnesium ions are also associated with “hard” waters. It has long been understood that hard water is less corrosive than soft water (low levels of calcium and magnesium ions) because of this mechanism (Uhlig 1963).

The sulphate ion and the chloride ion have been identified as the most important dissolved anions in soil corrosion phenomena (Roberge 2008, National Highway Institute 2009, Jack and Wilmott 2011). Sulphates by themselves are considered relatively benign in their direct influence on the corrosion process (compared to chlorides), but are an essential component of corrosion by sulphate-reducing bacteria (see previous section).

Chloride ions support the reactions and acidification occurring inside pits and crevices, (and possibly even the “crevice” shown in Figure 3.3). Chloride ions are drawn into pits due to a build-up of positively charged ferrous ions at the anodic surface. The anions are required to maintain electro-neutrality and complete the electrical circuit of the localised corrosion cell (Lytle et al. 2005). It should be noted, however, that diffusing anions from the external environment (such as chloride) may not be necessary to maintain electro-neutrality in the pit. The aggressive ion may be provided by manganese (II) sulphide (MnS) inclusions in the cast iron itself (Wranglen 1971).

Earlier studies of the effect of chlorides on the long term corrosion rate showed that for steel corrosion the effect was minimal, although corrosion under oxidation conditions with chlorides led to greater mass loss (Melchers 2006a). A similar effect can be expected for cast iron long-term corrosion.

4.8 Temperature

The affect of temperature on corrosion rates has been discussed by Tomashov 1966. The rate of chemical reactions and diffusion processes will generally rise exponentially with an increase in temperature, in accordance with the Arrhenius equation. However, the actual corrosion rate in a soil will not normally follow this trend. For instance, an increase in temperature may also lead to drying of the soil, thereby changing a major factor (moisture content), which complicates matters. Even though the corrosion processes are dependant on temperature, in practice, temperature is not considered as a basic factor in soil corrosion. In fact, soil temperature is rarely (if ever) recorded during field investigations of soil corrosion. Tomashov (1966) believes that soil temperature becomes a basic factor only when extremes in temperature are involved, as when comparing corrosion in frozen soils with corrosion in unfrozen soils.

5. MODELLING APPROACH

As noted, the aim of this project is to develop a model which will predict the corrosion (thickness loss and pit depth) versus time of exposure for a set of given external soil conditions. The most important part of the model will be the *long-term* corrosion versus time behaviour. At this stage an overview of the approach is presented.

The basic processes controlling the corrosion rates were described in Section 3, and occur in sequential phases as time progresses. Mathematical models will be constructed to describe each phase of the corrosion process. All of the principal phases are diffusion controlled and will be modelled as such, using approaches that are already available in the literature. This approach is similar to the approach used for the modelling of immersion and atmospheric corrosion in marine

environments (Melchers 2006b, Melchers and Wells 2006). The models will be calibrated with long-term field data (collected during the project) and historical data from the literature and industry partner files. Historical data will be required to calibrate the short-term phases of the model.

For the purposes of this study the diffusion processes will be represented as a one dimensional process, i.e. perpendicular to the corroding surface (as shown in Figure 4). This approach should capture enough of the essence of the problem to be sufficient for engineering purposes. The one-dimensional approximation should even be adequate in the case of corrosion by differential aeration. For instance the short term rate will be modelled as one-dimensional diffusion of oxygen at the cathode, and the long-term rate will be modelled as one-dimensional diffusion of ferrous ions at the anode. As a first step, the differential aeration cases shown in Figures 5-7 will be considered.

For practical purposes the models will be reduced to a simpler form (as illustrated in Figure 9). Models of this type have been developed before (Melchers 2008). The parameters that define the models (r_0 , t_a , c_a , r_a , c_s , r_s) will be functions of the various soil parameters discussed in Section 4. For the prediction of the long-term corrosion loss in a particular environment, model parameters c_s , and r_s will be the most important.

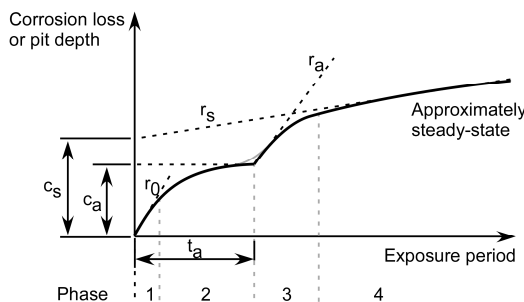


Figure 9 Corrosion loss-exposure time model for corrosion of iron in unsaturated soils, showing principal phases and main model parameters

6. FIELD DATA COLLECTION REQUIREMENTS

In-situ field data of actual water pipes that have been under long-term exposure conditions is required to develop and calibrate the proposed models. Important information required for model calibration includes details of pipeline construction, installation and history such as: pipe type, age, original diameter, original thickness, burial depth, bedding type, coatings (if used), joint type, leak history and exposure time. Important data on external soil conditions is based on the review in Section 4. Data required will include: soil type, moisture content profile next to pipe (and fluctuations), water table level (and fluctuations), soil bulk density next to pipe, and perhaps soil resistivity, organic and nutrient levels for assessing potential bacterial influence, and water chemistry. Other important information about the external soil conditions that may be useful in model development is the identification of large lumps of dissimilar soils stuck to particular places on a pipe (as in Figure 7). In terms of pipeline condition the following information will be required: pipe wall original thickness, wall thickness loss profiles, pitting profiles, and graphitised zone thickness profiles, and the condition of external coating (if any used). Information on the rust product types would also be useful for identifying the corrosion mechanisms taking place.

For the field work component of the project, data is being collected from the exhumation of existing water pipes as they are recovered by the water authorities during the period of the project. Pipe samples and soil samples are recovered from pipe breaks and also from decommissioned pipes that have been donated to the project. It is also expected that data will be collected during scheduled pipe maintenance and scheduled condition assessment programs that are already performed by water authority partners. Soil samples also are collected, the depth of the water table measured, and thickness loss due to corrosion and pitting profiles measured. As a part of the research project, Sydney Water has provided a 1.5 km long CICL water pipe to test condition assessment tools and make observations of pipe deterioration. This pipe was installed in 1922 and has a nominal diameter of 600 mm. Sections of the CICL pipe line have been exhumed and sent to each University with soil samples for analysis.

To determine the extent of pipe corrosion (thickness loss profiles, pitting profiles, and graphitized zone thickness profiles) photogrammetric and laser scanning techniques are being used. When pipes are first exhumed either of these two techniques can be used to generate a 3D image of the pipe. Abrasive blasting is then used to remove the graphitized zone and expose the original metal surface. A 3D image of this surface is then created (an example is shown in Figure 10). Using these two 3D surfaces, an estimate of the original pipe surface (from records), and a reference surface for taking measurements from (being the inside of the pipe), thickness loss, graphitised zone, and pitting depth profiles can be determined. From these profiles, the maximum thickness loss and pits (with corresponding depth of graphitisation) will be used to calibrate the model.

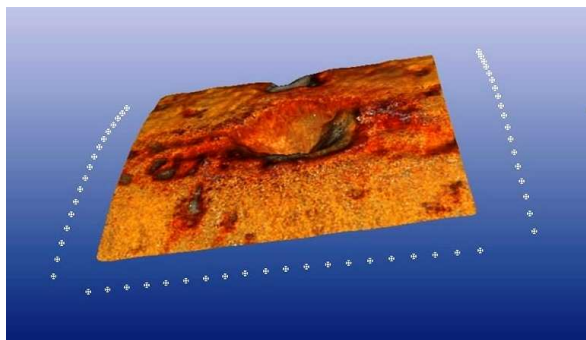


Figure 10 Photogrammetric representation of pitting on a 90 year old cast iron pipe with graphitised layer removed using abrasive blasting. The size of this section is approximately 20 cm x 20 cm. The approximate size of the pit depth and diameter are 20 mm and 60 mm, respectively.

7. SUMMARY AND CONCLUSIONS

1. The corrosion and failure of cement lined cast iron water mains is a significant problem for the Australian water industry. Herein a joint industry research project is outlined together with the overall approach being adopted for developing mathematical models for the description and prediction of the long-term corrosion losses and maximum pit depths and pitting patterns as a function of external soil and moisture properties. This includes the field collection requirements to provide data for model calibration.
2. The corrosion of cast iron (and other ferrous metals) in unsaturated soil appears to be similar to other forms of 'wet' corrosion and follows a monotonic bi-modal trend with time. In saturated soils a trend more closely resembling the typical power law model is likely to be observed.
3. For typical soil environments including unsaturated soils and saturated soils the long-term corrosion rate of cast iron most likely is hypothesised to be controlled by the rate of outward diffusion of ferrous ions through the graphitised zone and the rust products deposited on the external surface of the pipe. In this case the diffusion rate (and hence corrosion rate) is a function of the thickness, permeability and saturation level of these layers, which may vary in different soil environments.
4. The factors generally thought to affect soil corrosion include soil type, moisture content, degree of aeration, resistivity, pore water chemistry, microbiological activity, and temperature. However, clear correlation of these with corrosion has, to date, not been achieved. The most likely reason is not all possible factors have been considered, particularly for long-term corrosion. For this the major factors are likely to be moisture content (or degree of saturation), soil compaction (or soil density) and nutrient levels (for bacterial influence in saturated conditions). Very little data for these factors are presently available.

8. ACKNOWLEDGMENTS

This publication is an outcome from the Critical Pipes Project funded by Sydney Water Corporation, Water Research Foundation of the USA, Melbourne Water, Water Corporation (WA), UK Water Industry Research Ltd, South Australia Water Corporation, South East Water, Hunter Water Corporation, City West Water, Monash University, University of Technology Sydney and University of Newcastle. The research partners are Monash University (lead), University of Technology Sydney and University of Newcastle.

9. REFERENCES

- Caleyo F, Velázquez JC, Valor A, and Hallen JM (2009) Probability distribution of pitting corrosion depth and rate in underground pipelines: A Monte Carlo study, *Corrosion Science* 51 1925-1934.
- Cole IS and Marney D (2012) The science of pipe corrosion: A review of the literature on the corrosion of ferrous metals in soils, *Corrosion Science* 56 5-16.
- Crolet JL (1992) From Biology and Corrosion to Biocorrosion, (In) *Microbial Corrosion*, (Ed) CA Sequeira and AK Tiller, The Institute of Metals, London, 50-60.
- Doyle G, Seica MV and Grabinsky MWF (2003) The role of soil in the external corrosion of cast iron water mains in Toronto, Canada, *Can. Geotech. J.* 40 225-236

- Gummow RA and Wakelin RG (1993) A summary of the findings of recent watermain corrosion studies in Ontario, Institute for Research in Construction (Publishers) Ottawa, Ont.
- Gupta SK and Gupta BK (1979) The critical soil moisture content in the underground corrosion of mild steel, *Corrosion Science* 19 171-178.
- Jack TR and Wilmott MJ (2011) Corrosion by soils, (In) Uhlig's Corrosion Handbook, Third Edition (Ed) RW Revie, John Wiley, New York, 333-349.
- Jack TR, Wilmott MJ and Sutherby RL (1995) Indicator minerals formed during external corrosion of line pipe, *Materials Performance* 34(11) 19-22.
- Jakobs JW and Hewes FW (1987) Underground corrosion of water pipes in Calgary, Canada, *Materials Performance* 26(5) 42-49.
- Kreysa G and Schütze M (2008) DECHEMA Corrosion Handbook - Revised and Extended 2nd Edition. DECHEMA.
- LaQue FL (1958) The corrosion resistance of ductile irons, *Corrosion* 14 485-492.
- Lytle DA, Sarin P, and Snoeyink VL (2005) The effect of chloride and orthophosphate on the release of iron from a cast iron pipe section, *Journal of Water Supply: Research and Technology – AQUA* 54(5) 267-281.
- Makar JM, Desnoyers R, and McDonald SE (2001) Failure modes and Mechanisms in Gray Cast Iron Pipes, (In) *Underground Infrastructure Research*, June 10-13, Waterloo, Ontario, 1-10.
- Melchers RE (2006a) Modelling immersion corrosion of structural steels in natural fresh and brackish waters, *Corrosion Science* 48 4174-4201.
- Melchers RE (2006b) Corrosion of mild steel immersed in seawater, *Journal of Infrastructure Engineering (ASCE)* 12(3) 154-162.
- Melchers RE and Wells T (2006) Models for the anaerobic phases of marine immersion corrosion, *Corrosion Science* 48 1791-1811.
- Melchers RE (2008) The critical involvement of anaerobic bacterial activity in modelling the corrosion behaviour of mild steel in marine environments, *Electrochimica Acta* 54 80-85.
- Melchers RE (2009) Experiments, Science and Intuition in the development of models for the corrosion of infrastructure, (In) *Proc. Corrosion & Prevention*, Nov 15-18, Coffs Harbour, Australia, PF Thompson Memorial Lecture.
- Melchers RE (2011) Modelling long-term corrosion of mild steel in unpolluted fresh and sterile seawaters, (In) *Proc. 18th Intl. Corrosion Congress*, Nov 20-24, Perth, Australia, Paper 156.
- Melchers RE (2012) Long-term corrosion of grey cast iron in marine environments, (In) *Corrosion and Prevention*, Nov 11-14, Melbourne, Australia.
- National Highway Institute (2009) Report No. FHWA-NHI-09-087, Corrosion/ Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, National Highway Institute, Washington.
- Nicholas D and Moore G (2009) Corrosion of ferrous watermain: past performance and future prediction – a review, *Corrosion and Materials* 34(2) 33-40.
- O'Day DK (1989) External corrosion in distribution systems, *Journal American Water Works Association* 81(10) 44-52.
- Ohsaki Y (1982) Corrosion of steel piles driven in soil deposits, *Soils and foundations* 22(3) 57-76.
- Rajani B, Makar J, McDonald S, Zhan C, Kuraoka S, Jen C-K and Viens M (2000) Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life, American Water Works Association Research Foundation (Publishers), Denver, Colorado.
- Roberge PR (2008) Corrosion engineering principles and practice, Mc-Graw-Hill (Publishers), New York.
- Romanoff M (1957) Underground Corrosion, National Bureau of Standards Circular 579, US Government Printing Office (Publishers), Washington DC.
- Romanoff M (1962) Corrosion of Steel Pilings in Soil, National Bureau of Standards Monograph 58, U.S. Department of Commerce (Publishers), Washington, DC.
- Rossum JR (1969) Prediction of pitting rates in ferrous metals from soil parameters, *Journal American Water Works Association* 61 305-310.
- Schlesinger WH (1997) Biogeochemistry: An Analysis of Global Change. 2nd ed. Elsevier Academic Press (Publishers) Amsterdam.

Schulze ED and Mooney HA (1993) Biodiversity and ecosystem function, Springer-Verlag (Publishers) New York.

Tomashov ND (1966) Theory of Corrosion and Protection of Metals: The Science of Corrosion, Macmillan (Publishers), New York.

Uhlig HH (1963) Corrosion and Corrosion Control: an introduction to corrosion science and engineering. 2nd ed. John Wiley and Sons (Publishers), New York.

ASTM (2011) D2487-11, Standard practice for classification of soils for engineering purposes (unified soil classification system). Book of Standards Vol. 04.08. West Conshohocken, PA: ASTM International.

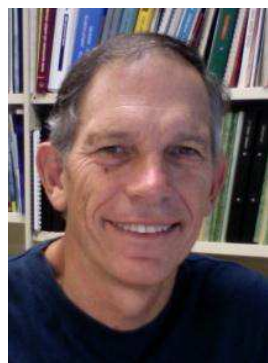
von Wolzogen Kuhr CAH and van der Vlugt LS (1934) Graphitization of cast iron as an electrochemical process in anaerobic soils, Water (den Haag) 18 147-165 (in Dutch). Translation in Corrosion (1971) 17 293-299.

Wranglen G (1971) Active sulfides and the pitting corrosion of carbon steels, (In) Localized Corrosion, Dec 6-10, Williamsburg, Virginia, 462-476.

10. AUTHOR DETAILS



Robert Petersen is a Research Associate in the Centre for Infrastructure Performance and Reliability at the University of Newcastle, Australia. He holds a BE (Civil Engineering, 2005) and a PhD (2009), both from the University of Newcastle. His PhD research was in the area of mathematical modeling of the behavior of structural masonry under various loading conditions. His current research interest is the corrosion of cast iron and steel water mains buried in soil.



Robert E Melchers is Professor of Civil Engineering and Australian Research Council Professorial Fellow at The University of Newcastle, Australia. He holds a BE and MEngSc from Monash University, a PhD from the University of Cambridge, UK and is a Fellow of the Australian Academy of Technological Sciences and Engineering. He was awarded the 2004 TP Hoar Prize (Institute of Corrosion, UK) (with Robert Jeffrey), the 2007 Guy Bengough Award (Institute of Materials, Minerals and Mining, UK), the Marshall Fordham prize (Australasian Corrosion Association) in 1999, 2002 and 2007 and the ACA Corrosion Medal in 2009. His research interests include structural reliability and marine corrosion.