### Activity 3 - Methods for Predicting Pipe Corrosion

#### 1. Introduction

Traditionally water pipes were often made from cast iron. Internally many of them have a cement lining intended to prevent internal corrosion and in most cases this is successful. The main problem for older cast iron pipes is external corrosion. Corrosion of pipes buried in the ground sometimes occurs rather quickly and often is very uneven (seen as pitting, such as shown in Fig. 1) yet others have been found to survive and to remain operational for many decades. There are some cast iron water pipes still in operation after more than 100 years in the ground.

Activity 3 focuses on developing simple mathematical models for predicting such corrosion. It uses data about the pipe and its operational and soil environment. This includes soil moisture content and the possibility of microorganisms attacking the cast iron or steel. The factors known to be involved are reviewed in Petersen and Melchers (2012).

Corrosion is an electro-chemical process and accordingly much of the emphasis in the study of corrosion has relied on electrochemical measurement techniques. Such techniques are attractive because the corrosion processes can be accelerated. In current industry practice electrochemical techniques are used by some water utilities to predict the likely long-term life of a pipe. The present Fact Sheet compares the electrochemical techniques with the approach being employed for Activity 3 and outlines the advantages and disadvantages of each.

The main electrochemical techniques that have been applied for studying the corrosion of cast iron pipes in the ground are:

(a) (Linear) Polarisation Resistance,

(b) Electrochemical Impedance Spectroscopy.

A brief overview of each of these is given below but first a short review of the corrosion process for ferrous metals may be helpful.

#### 2. Corrosion Basics

Corrosion of metals in water in the presence of oxygen (air) is governed by electrochemical reactions of the form

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\begin{align*}
\text{anodic reaction} & : \ Fe \rightarrow Fe^{2+} + 2e^- \quad (1) \\
\text{cathodic reaction} & : \frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH^-) \quad (2) \\
\text{overall} & : Fe + \frac{1}{2} O_2 + H_2O \rightarrow Fe(OH)_2 \quad (3)
\end{align*}
\]

These reactions usually occur at separated locations on a surface. To make them work together involves the transfer of electrons between them, with the metal oxidation reaction (1) occurring at what are known as anodes, and the (cathodic) reaction (2) occurring at what are known as the cathodes. The transfer of electrons occurs through the metal (which is much more conductive than the fluid in the soil). The net result is the overall reaction (3) where Fe(OH)₂ is the ferrous-oxihydroxide that is the precursor of all rusts normally seen in practice. The rate at which the corrosion reaction occurs is determined by the equilibrium between these two reactions. It implies electron flow from reaction (1) to (2). The flow of electrons is the result of the electrochemical potential that Fe possesses, relative to other materials and usually measured relative to some standard electrode. The details are not critical to the discussion (see text books). In unimpeded situations the kinetic rates at which the two reactions (1) and (2) can occur will determine the corrosion rate (i.e. the rate of transfer of electrons between them). This rate can be estimated from LPR and EIS analyses.
3. Linear Polarisation Resistance (LPR)

In the linear polarisation resistance technique a sample of the soil is taken in the vicinity of the pipe and (in the most common approach) an electrical potential is applied across this sample using steel or similar electrodes. The moisture content of the soil sample is controlled. Also, there is no attempt to use cast iron as part of the test. All emphasis is on the soil. When the applied potential is equal to the potential of the metal there will be no corrosion current. During the LPR test small variations of potential to the soil-metal system are applied and the resulting electrical (i.e. corrosion) current is measured for each such potential. The ‘polarisation resistance’ is then given by dividing the change in potential by the change in current (cf. Ohm’s law). This assumes linearity of the relationship but this approximation is close enough for small changes in potential (typically +/-10mV). The overall theory is a little more complex than this and can be seen in most standard corrosion texts (Jones 1996, Uhlig and Revie 1985). The polarisation resistance can then be used to estimate the corrosion rate, although often the polarisation resistance value itself is used as an estimate of resistance to corrosion.

The most important assumption underlying LPR is that it assumes the corrosion rate is controlled by reaction kinetics, that is, those of reactions (1) and (2). This is the case at the very beginning of the corrosion process but in practice and particularly for longer-term exposures there are likely to be some limitations. For example, the rate at which O₂ can arrive at the metal surface can be limited by mill scale effects and by the build-up of rusts. These cause the corrosion rate to be limited by diffusion effects. There also is the possibility of surface defects or surface composition differences. The latter may initiate localised corrosion or pitting effects. LPR cannot separate these from uniform or general corrosion. Various aspects of the use of LPR for application to cast iron pipe corrosion have been discussed, for example by Dafter et al. (2012), including the need to calibrate the outcome of LPR to long-term corrosion losses and pitting.

4. Electrochemical Impedance Spectroscopy (EIS)

EIS uses alternating current rather than direct current to do essentially the same as LPR. As a result it uses impedance rather than resistance to relate applied (alternating) potential to the measured (alternating) current. The results usually are plotted on a so-called Nyquist plot that also accounts for the current being 90° out of phase with the applied potential. The details are more complex than for LPR and can be found in standard corrosion texts. Application to cast iron pipe corrosion has been discussed by Goodman et al. (2013). The results of EIS need to be calibrated to field experience to make estimates of long-term corrosion damage.

5. Relationship between short and long-term corrosion

Examination of the corrosion loss and pit depth data for cast iron samples buried in the soil (Romanoff 1957) has shown that the trend is not a simple one (Fig. 2) (Melchers 2010). Similar trends have been found for cast iron exposed to seawater, fresh water and to the atmosphere (Melchers 2013). There is also information that for seawater conditions the water quality may have a serious effect on the corrosion losses in the longer term (Melchers et al. 2013). Both these observations are considered to be relevant also to cast iron pipes buried in the ground.

For long-term exposures (say 30-100 years) both the region of interest and the rate of corrosion of interest are shown at top right of Fig. 2. The corrosion processes in that region occur under (and within) the so-called graphitized layer. It consists mainly of graphite from which the iron has been corroded away and replaced by iron oxides, leaving a weak layer with essentially the same shape as the original surface of the pipe. The presence of this layer means that the corrosion rate is controlled entirely by diffusion processes. This means that the rate-controlling processes are completely different to those that control the rate measured by LPR and by EIS. As noted these are controlled directly by the kinetics of the anodic and cathodic reactions (1) and (2). The rate measured by LPR and by EIS is shown, schematically, in the lower left corner of Fig. 2, that is, near t = 0. It follows that there is a question of how the LPR and the EIS measurements relate to the long-term corrosion rate. Correlation between LPR and EIS results and actual observations of pipe corrosion have been undertaken for (LPR) (Dafter 2012, 2013) and are also proposed (EIS) but since the rate controlling processes are different, the quality and applicability of correlations are not necessarily clear. Recent work (Dafter 2013) has shown that any correlation is likely to be specific for a class of pipe and for a narrow range of soil types.

Figure 2. Longer-term trending of pitting corrosion as a function of exposure period showing the estimated long-term trend and the region where electrochemical tests are performed.
6. Activity 3 - Modelling

Rather than correlating LPR and EIS results with field observations, a more direct approach is to consider the rate controlling processes governing long-term corrosion and to use the underlying corrosion trends (such as shown in Fig. 2) to develop a mathematical model for long-term corrosion with influencing factors used to calibrate the model. The philosophy and approach to data collection and model calibration is outlined in Petersen and Melchers (2013) and Fact Sheet No. 14.

References


Partners

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