LONG-TERM CORROSION OF BURIED CAST IRON
WATER MAINS: FIELD DATA COLLECTION AND
MODEL CALIBRATION

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Abstract
The external corrosion of buried cast iron water mains is a significant problem for the Australian Water Industry. To improve maintenance and replacement strategies for these mains the water industry requires a method to estimate their remaining service lives. Predictions of long-term corrosion losses, pit depths and pitting extents are therefore required. A conceptual model for the prediction of long-term corrosion has been developed and the external soil conditions influencing corrosion were identified in a previous study. To calibrate the model, long-term data of corrosion (average losses and maximum penetration) and associated soil parameters for pipes in service is required. Field data has been collected at 18 condition assessment sites within Hunter Water Corporations network. This paper presents the field observations from the first 11 sites, the model calibration procedure and results of the calibration. The evidence gathered in this work suggests that the long-term maximum corrosion penetration increases with increasing soil wetness (measured using degree of saturation) for the sites investigated. The initial model calibration produced model parameters for cast iron pipes buried at standard depths in relatively homogeneous, low-permeability, soils with degrees of saturation equal to 0.66 and 0.76.

Keywords
Cast iron; water pipe; soil; long-term; external corrosion; model

INTRODUCTION
The external corrosion and failure of cement lined cast iron water mains is a significant problem for the Australian water industry. In 2011 a joint industry research project commenced, aimed at improving methods to predict pipe remaining service life. A number of industry partners and 3 universities are involved in the project (see Acknowledgements). The role of The University of Newcastle in the project is to develop models for the description and prediction of the long-term corrosion losses and maximum pit depths of cast iron (and also steel) buried in soil. The present paper describes aspects of this work.

The processes controlling the long-term corrosion of cast iron buried in a soil and the external soil conditions influencing long-term corrosion were reviewed in Petersen and Melchers (2012). Corrosion of cast iron (and other ferrous metals) in a soil appears to be ‘wet’ corrosion and was shown to follow a bi-modal trend with time (Figure 1), generally similar to what has been observed also for steels. The stages of the bi-modal behaviour were described earlier (Petersen and Melchers 2012).

For future life prediction of cast iron pipes both the magnitude of the long-term corrosion loss and rate of future corrosion are of most interest in practice. This includes average corrosion and maximum pit depth and pit area. A simple, practical model for the prediction of long-term corrosion (either maximum or average corrosion loss, and also pit depth) as a function of time can be obtained by bounding the bi-modal model as shown in Figure 1 (Petersen and Melchers 2012). The model parameters $c_s$ and $r_s$ are expected to be functions of the soil environment surrounding the pipe, including soil moisture.
To calibrate the long-term corrosion model, field data from actual pipes under long-term service conditions is required. A field work program has begun to collect data for model development and calibration. The field work procedure, data collected at each site, and the results from recent field work, is presented in this paper. Details of an initial model calibration, using the data collected from recent fieldwork, are also given.

FIELD WORK METHOD

The University of Newcastle was invited to visit a number of recent pipeline condition assessment sites within Hunter Water Corporation’s network to collect data for model development. These works were conducted by Hunter Water Australia and involved the exhumation and subsequent abrasive blasting of selected pipe sections to assess their condition. To date, data for model development has been collected from 11 water main sites and 7 sewer main sites. Results from the water main sites are presented in this paper. An outline of the data collection strategy is provided in this section.

At each site, information was recorded on the pipe details (including manufacture type, nominal diameter, and pipe wall thickness), exposure time and environment (ground cover, bedding and backfill conditions, burial depth and presence of groundwater) (see Table 1 later). Additional information on pipe section length, joint type, internal lining information, and presence of an external coating was also recorded.

Soil samples were collected at each site and sent to an external laboratory for testing to characterise the soil environment surrounding the pipe. A 5 kg amount of soil was sampled from the exposed face of the excavated pit next to the exposed pipe (Figure 2a). The soil sample was excavated with a pick axe and placed into a sealed plastic bag, which was then placed into a cool insulated container for transport to the laboratory. These samples were analysed at SESL laboratories in Sydney for the following properties: texture class, permeability class, moisture content, pH, resistivity, chloride, sulphate, nitrate, and phosphate content, and total organic carbon (TOC).

In addition to the samples taken for analysis at SESL, samples were also collected by the second author for his own independent studies. As a part of his studies he determined the moisture content of the soil in-situ and at field capacity, and these values were used as additional data for this project. A cylindrical core sample of soil was also taken next to the pipe with a thin walled metal tube (in the same location as shown in Figure 2a) by the first author. From this sample the bulk density (mass of soil/volume of soil), moisture content (mass water/mass soil), and porosity (volume voids/volume soil) were determined. The degree of saturation of the soil (volume water/volume
voids) was then determined using the calculated porosity and an average of the three moisture contents determined by the independent testers (SESL, first author, and second author). Methods to determine the bulk density, moisture content, porosity and degree of saturation are well-known and are described in detail in many soil mechanics or soil sampling and testing textbook, such as Tan (2005).

Following abrasive blasting at each site the external corrosion losses were quantified. Where possible, a selected portion of each pipe (typically a metre in length) was scanned using a handheld Creaform Laser Scanner to accurately map (in 3D) the external surface of the pipe. The general procedure involved randomly placing adhesive positioning targets onto the pipe surface (approximately 5-10 cm apart), calibrating the scanner, and then performing the scanning operation. The scanning operation involved pointing the handheld device at the pipe surface and sweeping across the area to be scanned (Figure 2b). The time taken to apply targets and scan each pipe was approximately one hour. A scanning resolution of 2 mm was selected for this work.

In addition to the laser scanning, each pipe was inspected visually and the deepest pits were measured using a pit depth gauge. Due to the constraints of the laser scanner and workplace health and safety (WHS) issues at certain sites (for example, the water table preventing exhumation of the entire pipe) it was not always possible to obtain a laser scan of each pipe or indeed the whole pipe. In these cases, manual techniques, including use of a pit depth gauge, were used to supplement or replace the laser scanning results.

The 3D surface scans were later post-processed to determine maximum and average corrosion losses. The software program supplied with the laser scanner was used to determine and map relative corrosion depths over the surface of the pipe. Corrosion depth versus axial and circumferential position were exported into tables of 2 x 2 mm grid spacing, and imported in Microsoft Excel for analysis. The maximum penetration and average corrosion loss were determined from the tabulated data. Note that additional corrosion parameters can be determined from the data produced by the scans, such as the statistical variation of maximum losses, volume of corrosion losses, and area of pits and pit clusters.

![Figure 2. Photographs of pipe in excavated trench showing soil sample collection location and surface scanning in progress (after abrasive blasting).](image-url)
FIELD WORK RESULTS
A summary of the data collected from field sites is presented in Table 1. The pipes inspected covered the complete range of cast iron pipe types used in Australian pipe-laying practice covering a period of 36 to 129 years. The pipes are differentiated by manufacture process and include: vertically sand cast; deLavaud; Super deLavaud; and Yennora spun. Note that information on Australian pipe-laying practice is summarised in Nicholas and Moore (2009). All of the pipelines inspected were buried under grass easements, and all sites were backfilled with native soil (as was the common practice before 1960, see Nicholas and Moore 2009). A select sand backfill may have been used at sites RT1 and RT2; however the backfill material was indistinguishable from the surrounding native sandy soil. Soil groundwater conditions ranged from no observed water table to pipes being half-submerged.

The majority of soils were inorganic clays, with inorganic sandy soils encountered at only a few sites. The levels of pH, chloride content, and sulphate content, measured at all sites, are considered non-aggressive to steel that is in contact with disturbed soil according to AS2159:2009 (Standards Australia, 2009). The levels at which they are considered to become mildly aggressive are pH < 5, chloride content > 5000 mg/kg, and sulphate content > 1000 mg/kg. Therefore it is unlikely that these are significant factors affecting the corrosion of these pipes. The moisture content presented in Table 1 is an average of the three values determined by SESL, and the first two author's independent tests.

At most sites the soil in contact with the pipe was relatively uniform, and the soil sampled next to the pipe was considered representative of the soil surrounding and touching the pipe. At two sites, however, the soil surrounding (touching) the pipe varied greatly. At site MC3 the soil surrounding the pipe was made up predominantly of a sandy soil, but also included clay lumps (of varying sizes) interspersed throughout. The worst identified location of corrosion on this pipe was found underneath a clay lump stuck to the surface of the pipe. Only this clay soil was sampled for analysis. At site MC5 the soil changed from clay at one end of the excavated pit, to sand at the other end of the excavated pit (pit length approximately 3 m). Both the sand and clay soils were sampled, as was a soil sample under the water table at the site.

The location, depth of maximum corrosion penetration, and corrosion form was recorded for all pipes. In some cases only a portion of the pipe was inspected due to restrictions on site (such as a high water table). These cases are identified in Table 1. External surface scans of five pipes were conducted (MC1, MC4, WS2, WS4, WS5), from which the maximum corrosion penetration and average loss were determined. Only the maximum penetration is presented and discussed in this paper. Figure 3 shows photos of pipes MC4 and WS4 after external blasting and 3d scans of these pipes.

The deepest corrosion was observed at the base of many pipes (180 degrees rotation from the top of the pipe), which is common experience (Romanoff 1957). However, this was not observed for all pipes. Some pipes were not inspected on the base due to site restrictions (MC3 and MC5), and the location (around the circumference) of maximum corrosion on pipe WS2 was not known (see Table 1 footnotes).

Two forms of corrosion loss were identified: isolated pits and general patches of corrosion or interacting pit clusters. An example of corrosion identified as isolated pitting is shown in Figure 3c on a 46 year old Yennora spun CI pipe. An example of general/interacting pit cluster corrosion is shown in Figure 3d on a 130 year old vertically cast CI pipe. In general isolated pits were observed on younger pipes (Yennora spun) and the general/interacting pit cluster corrosion was observed on
the older pipes of the other manufacture types. It is possible that manufacturing type may affect corrosion form; however it seems more reasonable that corrosion form is more greatly affected by exposure time. It is suspected that initially individual pits form, but over time these pits join together to create clusters. Environmental conditions are also likely to influence corrosion form. The factors influencing corrosion form require further investigation.

A remaining bitumen external coating was observed on pipes RT1, RT2 and MC3. The remaining bitumen coating was identified by a shiny black appearance. No remaining coating was observed on the other pipes (or it was not clear). This does not mean that a coating was not originally applied, however. It is likely that the vertically sand cast pipes (pre 1929) had a thick bitumen coating applied by hot dipping after casting. Pipes manufactured after 1929 (or less than 84 years old) were specified to have a painted bitumen coating (considered to offer little protection, Nicholas and Moore 2009), but whether or not this was applied to a particular pipe was difficult to determine.

It is expected that the most significant factor influencing long-term corrosion rate and extent is the degree and time of wetness of a soil. To define the degree of wetness of a soil the degree of saturation is likely to be the most useful quantitative measure (more useful than soil moisture content alone – see Gupta and Gupta 1979). The degree of saturation is equal to the volume of water divided by the volume of voids in a soil. For the purposes of studying the effect of soil moisture on long-term pipeline corrosion it was assumed that the soil moisture content measured in the field was equal to the long-term average moisture content. This assumption was considered reasonable for the pipes buried in clay soil sites, as the variation (in time) of soil moisture content at depths below approximately 800 mm in clay soils is typically low (less than 5-10%) (Rajeev et al 2010). This is not the case for sandy soils, so the sites in sandy soils were left out of the following analysis. Most soils were collected at depths at least 800 mm deep. At the clay sites the measured in-situ moisture content was close to the experimentally determined field capacity. The field capacity is typically assumed to represent the long-term average in-situ moisture content in a soil above the water table. This provides additional confidence that the in-situ moisture content is a good approximation of the long-term moisture content. Note that the in-situ moisture content was used (with the bulk density calculations) to determine the degree of saturation of the soil.

Figure 4 shows a plot of maximum penetration versus exposure time for the inspected pipes. Each data point is labelled with the site name and degree of saturation (Sw). Note that the sandy soil sites (RT1 and RT2) and the non-typical sites (those with site specific factors – MC3, MC5, & WS2) were not considered in this analysis. Point KK3 is an additional data point from ongoing site investigations on sewer rising mains, and has been included for additional information. The degree of saturation of MC4 was revised to reflect the fact that the deepest pits were observed on the bottom of the pipe, which was in contact with the water table. The general data trend shown in Figure 4 suggests that the corrosion rate increases with increasing wetness, with the exception of the data point from WS1. The reason why the data point WS1 does not support this trend is unclear.
<table>
<thead>
<tr>
<th>Site</th>
<th>Pipe details</th>
<th>Environment</th>
<th>Soil properties</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Nominal Diameter (mm)</td>
<td>Thickness (mm)</td>
<td>Exposure time (yr)</td>
</tr>
<tr>
<td>RT1</td>
<td>YS</td>
<td>500</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>RT2</td>
<td>YS</td>
<td>500</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>RT3</td>
<td>SD</td>
<td>250</td>
<td>13.2</td>
<td>58</td>
</tr>
<tr>
<td>MC1</td>
<td>VC</td>
<td>450</td>
<td>16-18</td>
<td>90</td>
</tr>
<tr>
<td>MC3</td>
<td>SD</td>
<td>500</td>
<td>17</td>
<td>54</td>
</tr>
<tr>
<td>MC4</td>
<td>YS</td>
<td>300</td>
<td>11</td>
<td>46</td>
</tr>
<tr>
<td>MC5ᵇ</td>
<td>D</td>
<td>500</td>
<td>16-17</td>
<td>74</td>
</tr>
<tr>
<td>WS1</td>
<td>VC</td>
<td>375</td>
<td>17-20</td>
<td>129</td>
</tr>
<tr>
<td>WS2ᵉ</td>
<td>VC</td>
<td>375</td>
<td>17-20</td>
<td>129</td>
</tr>
<tr>
<td>WS4</td>
<td>VC</td>
<td>375</td>
<td>17-20</td>
<td>129</td>
</tr>
<tr>
<td>WS5</td>
<td>VC</td>
<td>600</td>
<td>22.2</td>
<td>83</td>
</tr>
</tbody>
</table>

Pipe type: VC=Vertically sand cast, D=deLavaud (AIS), SD=Super deLavaud (AIS), YS = Yennora spun CI; 
**Ground cover** G=grass; **Bedding/Backfill** N=native; **Burial depth** measured from ground surface to top of exposed pipe; 
**Groundwater** M=middle of pipe, B=touching bottom of pipe, -300 = 300 mm below bottom of pipe, no = not observed; 
**Texture class:** S = sand, LS = loamy sand, SC = silty clay, SCL = silty clay loam, SdC = sandy clay, LC = light clay; 
**Corrosion form** (subjective interpretation) I=isolated pits, G = general/interacting pit clusters, U = unknown.

ᵃ assumed ᵇ bedding/backfill could not be distinguished from native sandy soil  
ᶜ MC3 site: highly variable soil; sandy soil plus clay lumps. Corrosion damage was found under adhered clay lump. Clay soil was analysed. Only top half of pipe inspected. Not abrasive blasted.  
ᵈ MC5 site: variable soil; clay at one end of pit (max corrosion observed) and sand at opposite end. Three soil samples collected: clay, sand, & clay below wt. Properties of clay soil (at measured corrosion site) presented in table. Bottom of pipe not inspected. A hardwood and stone platform was observed underneath the pipe, indicative of wet ground conditions at construction  
ᵉ WS2 site: Pipe buried at another location for first 65 years of exposure. The pipe orientation was likely different at original site.
Figure 3. Photographs of pipes MC4 and WS4 after abrasive blasting, and 3d scans of corroded external surface. In the 3d scans the position of the white arrow indicates the top of the pipe and the contour plots represent pipe wall thickness loss (as a percentage of the original thickness).

Figure 4. Maximum penetration versus exposure period for inspected pipes. $S_w = \text{degree of saturation of soil adjacent to the pipe.}$
RELATING COLLECTED LONG-TERM DATA WITH HISTORICAL SHORT-TERM DATA AND INITIAL MODEL CALIBRATION

In order to calibrate the corrosion model, the collected long-term data needs to be related to short-term data under similar environmental conditions. Finding data sets under the same exact conditions is unrealistic. Instead, the approach taken here is to relate sites together based on the parameters that are considered to be most significant to long-term corrosion. These parameters being (in decreasing order of expected influence): moisture, nutrients, pH, compaction. In this paper sites are related by the first parameter moisture, which is defined with the degree of saturation of the soil. The other parameters are not considered yet, and at this stage are just considered to add some noise to the results.

The (relatively) short term data presented in Romanoff (1957) was used for this analysis. In this report corrosion versus time data is presented for cast iron pipes buried in 14 different soils for 14 years. Data for both average mass loss and maximum penetration is presented.

Romanoff collected a comprehensive set of soil data at each site. However, moisture content was not reported, instead a subjective, qualitative measure of the site drainage conditions were given (good, fair, poor, very poor). Romanoff did, however, report the apparent specific gravity and percentage air pore space of each soil, from which both the moisture content and degree of saturation can be estimated. For these calculations a soil particle density of 2670 kg/m³ was assumed. As before, it was assumed that the estimated moisture content and degree of saturation values were a good approximation of the long-term values. Results for soils with degree of saturation values of 0.66 and 0.76 were used to relate to the long-term data. Selected soil properties and details for these sites are provided in Table 2.

Table 2. Selected soil properties at Romanoff (1957) test sites

<table>
<thead>
<tr>
<th>Number</th>
<th>Soil Type</th>
<th>Drainage</th>
<th>pH</th>
<th>Air pore space (%)</th>
<th>Apparent specific gravity</th>
<th>Degree of saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>53</td>
<td>Cecil clay loam</td>
<td>Good</td>
<td>4.8</td>
<td>18.2</td>
<td>1.60</td>
<td>0.66</td>
</tr>
<tr>
<td>62</td>
<td>Susquehanna clay</td>
<td>Fair</td>
<td>4.5</td>
<td>14.9</td>
<td>1.79</td>
<td>0.66</td>
</tr>
<tr>
<td>55</td>
<td>Hagerstown loam</td>
<td>Good</td>
<td>5.8</td>
<td>15.5</td>
<td>1.49</td>
<td>0.75</td>
</tr>
<tr>
<td>65</td>
<td>Chino silt loam</td>
<td>Good</td>
<td>8</td>
<td>15.8</td>
<td>1.41</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The maximum penetration data (average values) of these soils are shown with the collected long-term data in Figure 5. Lines were drawn to connect the short and long-term data: soils 53 and 62 (Sw=0.66) were related to site RT3 and KK3 (Sw=0.66); and soils 55 and 65 (Sw=0.76) were related to site WS5 (Sw=0.76). The results from short term study appear to be consistent with the results from this longer term study. Also, the observed trend that corrosion increases with increasing moisture is also consistent between the data sets. This consistency adds confidence to the proposed approach for constructing the long-term corrosion (maximum penetration) versus time behaviour.

The model outlined in Section 1 was fitted to the data in Figure 5. The model fit results are shown in the figure and are as follows: for Sw =0.66, rs = 0.08 mm/yr and cs = 1.80 mm; for Sw = 0.76, rs = 0.10 mm/yr and cs = 2.46 mm.
Figure 5. Maximum penetration versus exposure period for inspected pipes. Plot includes: long-term results from the current study, short-term results from Romanoff (1957), and model fit.

SUMMARY AND CONCLUSIONS
This paper has presented preliminary results of a field study on the corrosion of cast iron pipes buried in soils. The following conclusions may be drawn from the study to date:

1. Long-term maximum corrosion penetration increases with increasing soil wetness (measured using degree of saturation) for the sites investigated.
2. Using long-term and short-term data from different data sets and using only the most significant parameters influencing corrosion appears to produce rational and consistent results based on degree of saturation to represent the moisture available for corrosion.
3. The initial calibration for model parameters is for cast iron pipes buried at standard depths in relatively homogeneous, low-permeability, soils with degrees of saturation equal to 0.66 and 0.76.

Further work is required for model calibration, including the collection of data from additional field sites and from historical studies and the analysis of non-typical cases that were removed from the present analysis.

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