LONG TERM CORROSION OF BURIED CAST IRON PIPES IN NATIVE SOILS

R.B. Petersen[1] and R.E. Melchers[1]
[1]Centre for Infrastructure Performance and Reliability, The University of Newcastle, Australia

SUMMARY: The corrosion of old buried cast iron water mains is a problem for the Australian Water Industry. To better manage their assets the industry requires a way of predicting the remaining service life of their pipes. In order to do this a predictive model of long-term corrosion loss with time is required. This paper describes ongoing work being conducted at The University of Newcastle to develop corrosion loss models for cast iron pipes in soils, as a function of exposure time and soil environment. A preliminary corrosion model was calibrated in a previous work, using a limited set of data collected from recent field work. This data base was extended in the current work by including data (of maximum pit depth and some soil properties) from historical condition assessments within the Hunter Water network. Previous studies by the authors (and others) indicate the significance of soil moisture content on the long-term corrosion loss and rate. At most sites soil moisture was only measured at a single point in time (or not at all), so the long-term average value of soil moisture (required for model calibration) was uncertain. To better estimate the average long-term soil moisture content, a simple climate-soil moisture model was developed. This paper presents the collected field data, describes the method for estimating long-term moisture content and presents the updated model calibration based on the additional data.

Keywords: Cast iron, Pipe, Soil, Long-term, External corrosion, Model, Moisture.

1. 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).

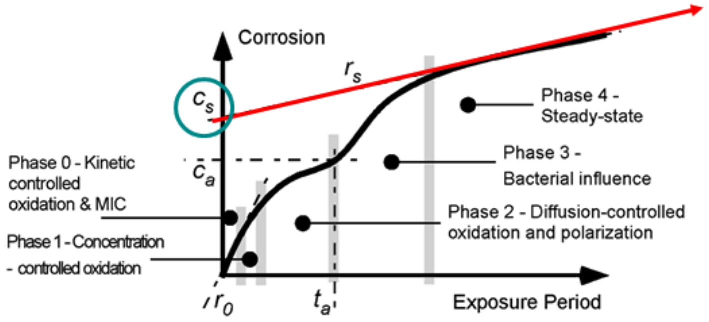

Figure 1 Bi-modal corrosion behaviour and long-term corrosion loss model

Long-term corrosion is controlled by the diffusion of reacting species through the corrosion rust product layer (and the rust-filled graphitised zone layer in cast iron) to the metal surface (Petersen and Melchers 2012). In the short term (Phase 1-2), under unsaturated conditions, corrosion takes place under aerobic conditions and oxygen is typically the rate limiting diffusing species (Tomashov 1966). The available experimental and theoretical evidence is that in the long-term (Phase 3-4) the corrosion takes place under anoxic conditions, with diffusion again being the rate limiting process. The species involved vary as corrosion continues.

In the very short term the corrosion rate will typically be determined to a large extent by the soil properties which affect the transport of oxygen to the surface of the metal, including soil texture, compaction, burial depth and saturation. In the long-term the corrosion rate will be determined by the soil properties which affect the transport of water to the surface of the metal, plus any other species required for the long-term mechanism to be sustained, such as an aggressive ion (see Petersen and Melchers 2012). These properties include soil texture, degree of saturation, soil compaction, some soil water chemical properties, and nutrients. In the long-term the main diffusion barrier is the rust product layer and rust-filled graphitised zone, so it is expected that the soil parameters affecting the growth and structure of this barrier will also have a large influence on observed long-term corrosion and corrosion rate. These properties include texture, degree of saturation, compaction, and soil water chemistry. A more detailed discussion on the long-term corrosion processes and factors that influence them is provided in 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 (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. The model parameters c_s and r_s are expected to be functions of the soil environment surrounding the pipe. The expected order of influence being: degree of saturation, nutrients, pH, compaction, based on the review of the long-term processes in Petersen and Melchers (2012).

To calibrate the long-term corrosion model, field data from actual pipes under long-term service conditions is required. A preliminary corrosion model was calibrated in a previous work (Petersen et al. 2013) using data collected at a number of condition assessment sites on cast iron pipes within Hunter Water Corporation’s network. 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 0.57, 0.66, and 0.76 (Figure 2). For this analysis the model was calibrated for only the degree of saturation of the soil. The degree of saturation was determined based on a moisture content determined at the time of inspection, and was assumed to represent the long-term average, which is not entirely correct. It was proposed, in the current work, to use a simple climate-soil moisture model to check the assumed long-term moisture content/degree of saturation at the sites.

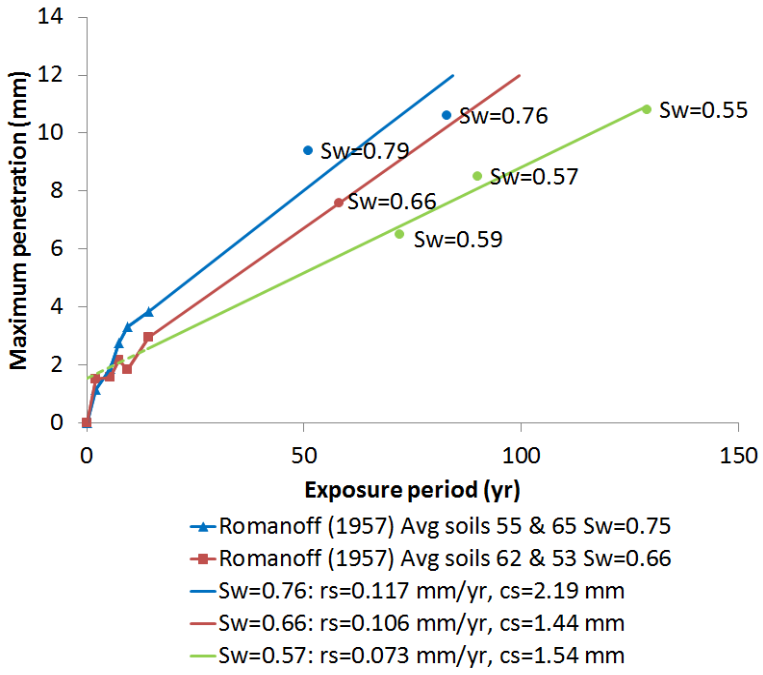

Figure 2 Maximum pit depth versus time models for native clay soils as a function of degree of saturation S_w. (Petersen et al. 2013)

The initial calibration was based on only a limited set of data (see Figure 2). To increase the amount of data for model calibration it was proposed (in the current work) to includes data from historical condition assessments within the Hunter Water network. However, at most of these sites soil moisture was only measured at a single point in time (or not at all), so the long-term average value of soil moisture (required for model calibration) was uncertain. To better estimate the average long-term soil moisture content, a simple climate-soil moisture model was developed as part of the present project. This paper presents the collected field data, describes the climate-soil model, its verification and estimates of the long-term moisture content at the condition assessment sites. The paper then presents the updated model calibration based on the additional data.

2. DATA

Details on the condition assessment sites used for the current work are summarised in Table 1. The moisture model described in the following sections was used to improve or make initial estimates of long-term moisture contents at these sites. Data in Set 1 refers to a subset of sites inspected during condition assessments within Hunter Water Corporation's cast iron water and sewer network conducted in 2013 and detailed in Petersen and Melchers (2013). The selected data comes from sites where the pipes were buried in native soil backfill. At these sites external corrosion loss data (including maximum pit depth) and data on soil properties was collected. Soil samples were collected and analysed for a range of properties including texture, density, moisture contents (in-situ, field capacity and wilt point), plus soil water chemistry parameters and soil water nutrient concentrations. Note that the wilt point is defined as the minimal point of soil moisture that a plant requires so that it does not wilt. This data was analysed previously in Petersen and Melchers (2013), and was used for the initial model calibration (as described above). Only the relevant parameters to the current study are shown in Table 1. For more details on the pipe and environment from this data set see Petersen and Melchers (2013).

Table 1 Selected data collected at condition assessment sites

Site	Soil*	Ground-water*	moisture content (% g/g moist soil)			porosity	Exposure period (yrs)	Maximum pit depth (mm)
			in-situ	wilt	field capacity			
Set 1								
MC1	SC	X	17.4	12.5	21.9	0.50	90	8.5
WS4	SdC	X	15.3	8.6	15.0	0.49	129	6.1
WS5	SC	X	17.7	12	21.0	0.41	83	10.6
KK3	C	X	21.9	16.4	30.5	0.56	72	6.5
DU2	C	B	20.9	11.8	22.5	0.45	47	8
BE2	C	-400	25.0	15.3	28.0	0.53	51	9.4
B1	C	X	17.0	10.8	20.3	0.50	129	10.8
B2	SdC	X	12.0	8.0	15.4	0.43	129	8.2
WS1	SC	X	20.2	13.8	24.3	0.46	129	6.5
RT3	SC	X	19.8	11.6	19.1	0.50	58	7.6
Set 2								
BS2	S	submerged	-	3.9	5.5	-	46	0
BS1	S	-400	-	0.7	0.9	-	52	2.1
MW3	SC	B	-	8.8	12.6	-	67	8.5
BR1	S	X	-	7.4	10.1	-	81	8.2
WV1	C	X	-	12.1	22.3	-	54	8.2
AP2	SC	X	-	18.7	35.2	-	94	7.8
AP3	SC	-300	-	13.3	23.7	-	42	5.7
RG1	C	-200	16.9	12.9	21.5	-	69	5
RG2 (1)	C	X	-	12.5	21.8	-	64	6.7
RG2 (2)	C	X	-	12.5	21.8	-	42	4.6
RG4	C	X	30.7	22.0	37.6	-	69	6.7
LB1	C	X	17.4	13.3	24.4	-	77	7.3
LB4	C	X	13.6	14.2	30.1	-	55	7.6

***Soil**: S = sand, SdC = sandy clay, SC = silty clay, C = clay; **Groundwater**: X = not observed, B = touching bottom of pipe, -400 = observed 400 mm below bottom of pipe.

Data Set 2 comprises data collected during condition assessments, also within Hunter Water Corporation's cast iron water network, but collected earlier, over the period 2007-2012. At these sites maximum pit depths were measured and general descriptions of the soil environment were made. Soil samples were also collected and from these samples the moisture content at wilt point and field capacity were determined. At some sites the in-situ moisture content was also determined.

3. CLIMATE SOIL-MOISTURE MODEL

To make estimates of soil moisture for those sites for which soil moisture was either not measured or about which a degree of doubt exists, a climate soil-moisture model was implemented for the present study. The model used is an adapted version of the simple bucket model for soil moisture simulation developed by Greve et al. (2013). This model calculates soil moisture variation with time by applying a water volume balance calculation over a volume of soil. A single bucket is used for the soil moisture simulation and therefore only a single value of saturation is determined across the soil profile. In this study the volume balance calculations were performed on a daily time scale.

A schematic of the model is shown in Figure 3. Essentially it consists of a bucket to represent a volume of soil with the only input being infiltrated rain water. This causes an increase in soil moisture (within the bucket). The volume of infiltrated rain water is equal to the lesser of the actual daily rainfall and initial infiltration capacity of the soil. Any volume of rainwater greater than the infiltration capacity goes to runoff and does not affect the moisture in the bucket.

Water is lost from the soil by evapotranspiration and drainage. To determine the daily evapotranspiration ET (in mm) Equation 1 is used:

$$ET = \begin{cases} 0 & for\ \theta \leq \theta_w \\ \frac{\theta-\theta_w}{\theta_c-\theta_w} ET_p & for\ \theta_w < \theta \leq \theta_c \\ ET_p & for\ \theta > \theta_c \end{cases} \tag{1}$$

where θ is the volumetric soil moisture content, θ_w is the soil moisture content at plant wilting level, θ_c is the critical soil moisture content, and ET_p is the potential daily evapotranspiration. The critical soil moisture content is defined as the quantity of stored soil moisture below which water uptake is impaired and the plant closes its stomata. The critical soil moisture content θ_c is determined using Equation 2 (van Diepen et al 1988):

$$\theta_c = (1-p)\left(\theta_{fc} - \theta_w\right) + \theta_w \tag{2}$$

where θ_{fc} is the volumetric soil moisture content at field capacity, and p is the soil water depletion fraction as a function of potential evapotranspiration (ET_p). Values of p vs ET_p are provided in Doorenbos et al. (1978).

The rate of drainage Q (mm/day) is determined using Equation 3 (Clapp and Hornberger 1978):

$$Q = K_s \left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{3}$$

where K_s is the hydraulic conductivity at saturation, θ_s is the saturation soil moisture, and b a pore size distribution parameter. Note that the model assumes that if the water volume in the bucket exceeds the capacity of the bucket (equal to the soil pore volume), the additional water will overflow from the bucket. Also, the model does not take into account the influence of a groundwater table on the moisture content, and therefore the model is only suitable for simulating moisture content in the unsaturated zone. Thus the model is not suitable for sites where the pipe is partially or fully submerged by a water table.

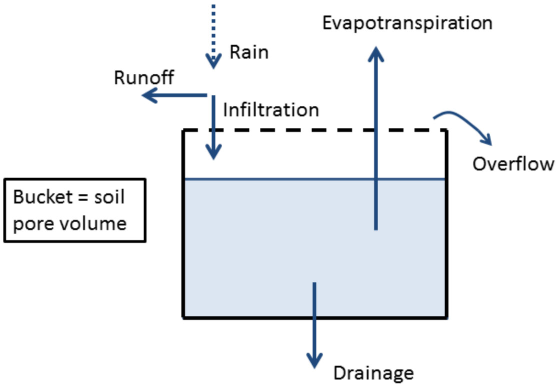

Figure 3 Schematic of climate soil-moisture model

4. MODEL VERIFICATION

The model was verified using field data collected by Kodikara et al. (2014) from two sites in Victoria, Australia. The data collected at these sites included soil data, and weather and soil moisture data, monitored over the time period Feb 2009 to May 2011. The soil data included those shown in Table 2, and were determined from soil samples taken on site. Kodikara et al. (2014) monitored various weather parameters including air temperature, humidity, wind speed, radiation, and rainfall. Soil moisture was monitored across the soil profile (to a depth of 1600 mm) using both a Neutron moisture meter and ThetaProbes. The Neutron moisture meter is a moisture meter utilising neutron scattering. It consists of a cylindrical probe which is connected to a case containing a power supply, display, keypad and microprocessor. During use the probe is lowered into an access tube in the soil for readings. The Theta probe is device that consists of a waterproof housing which contains the electronics, and attached to one end has four sharpened stainless steel rods that are inserted into the soil. The ThetaProbe measures volumetric soil water content by determination of the apparent dielectric constant.

Table 2 Input data and results of model verification

Site	Average soil properties						Long-term average vol. moisture content		
	θ_w	θ_{fc}	Porosity ($\emptyset$)	Infiltration rate (mm/hr)	K_s (mm/hr)	b^*	$Model$	$Field$	$\frac{Model}{Field}$
Altona North	0.31	0.46	0.49	0.07	0.007	11.4	0.32	0.31	1.03
Fawkner	0.28	0.40	0.44	0.1	0.006	11.4	0.29	0.30	0.98

* Recommended value for clay (Clapp and Hornberger 1978)

The weather parameters (not including rainfall) were used in the current study to determine the daily potential evapotranspiration using the Penman-Monteith equations (Zotarelli et al 2013). The input data (daily rainfall, daily evapotranspiration, and soil parameters – see Table 2) were used with the model to produce a plot of volumetric soil moisture content versus time. From this plot the long-term average soil moisture content was determined. A depth of 1 m was used for the bucket. The model was rerun with different bucket depths, and it was found that the model results were not sensitive to this parameter. The long-term average moisture content measured in the field was also determined. The results are summarised in Table 2. The simulated moisture content was very close to the field observed moisture content. On this basis it was assumed that the model could be used with confidence to check/estimate long-term average moisture contents at the condition assessment sites.

5. SOIL MOISTURE ESTIMATION AT CONDITION ASSESSMENT SITES

The verified climate soil-moisture model was used to check, and in some cases estimate, the long-term moisture contents at the condition assessment sites. For data set 1, soil parameters θ_w, θ_c, and porosity $\emptyset$ were determined from tests on soil samples taken from the condition assessment site. Values for the saturated hydraulic conductivity K_s and the pore size distribution parameter b were assumed based on the soil type determined at the site and recommendations in Clapp and Hornberger (1978).

For data set 2, soil parameters θ_w and θ_c were determined from tests on soil samples taken from the condition assessment site. Values for the porosity $\emptyset$, the saturated hydraulic conductivity K_s and the pore size distribution parameter b were assumed based on the soil type determined at the site and recommendations in Clapp and Hornberger (1978). The infiltration rate for both data sets was assumed equal to the saturated hydraulic conductivity K_s.

Daily rainfall and daily evapotranspiration data was sourced from the Bureau of Meteorology website (Bureau of Meteorology, 2014). In general, 3 years of data (close to the time of inspection) was collected from the closest weather monitoring station to the specific site. This weather data was assumed to provide a close representation of the long-term weather conditions at the sites.

The model, with a bucket depth of 1m, was used to determine the long-term average moisture content at each site. This value was then converted into a degree of saturation value (S_w) using the porosity (to be used later for model calibration). The input soil properties and the simulated and field observed saturation values are shown in Table 3. Note that the field determined S_w was based on a moisture content determined from soil sampled at the depth of the pipe during the time of inspection (one point in time) and the field determined or estimated porosity.

Table 3 Soil moisture estimation at condition assessment sites

Site	Soil*	Ground-water*	θ_w	θ_{fc}	$\emptyset$	K_s (mm/hr)	b	$Model\ S_w$	$Field\ S_w$	$\frac{Model}{Field}$
Set 1										
MC1	SC	X	0.19	0.38	0.50	3	10.4	0.59	0.57	1.04
WS4	SdC	X	0.13	0.24	0.49	7	10.4	0.47	0.49	0.96
WS5	SC	X	0.21	0.41	0.41	3	10.4	0.68	0.76	0.89
KK3	C	X	0.23	0.51	0.56	4	11.4	0.63	0.59	1.06
DU2	C	B	0.19	0.43	0.45	4	11.4	0.63	0.85	0.74
BE2	C	-400	0.23	0.49	0.53	4	11.4	0.62	0.79	0.78
B1	C	X	0.16	0.34	0.50	4	11.4	0.52	0.55	0.95
B2	SdC	X	0.13	0.28	0.43	7	10.4	0.52	0.49	1.05
WS1	SC	X	0.23	0.46	0.46	3	10.4	0.68	0.78	0.87
RT3	SC	X	0.18	0.32	0.50	3	10.4	0.55	0.66	0.84
Set2										
BS2	Sand. Pipe submerged. S_w = 1. No model.									
BS1	S	-400	0.01	0.02	0.40	633	4	0.13	X	X
MW3	SC	B	0.15	0.22	0.43	7	10.4	0.51	X	X
BR1	S	X	0.13	0.18	0.40	633	4	0.33	X	X
WV1	C	X	0.19	0.39	0.50	4	11.4	0.60	X	X
AP2	SC	X	0.21	0.50	0.50	3	10.4	0.61	X	X
AP3	SC	-300	0.21	0.42	0.50	3	10.4	0.58	X	X
RG1	C	-200	0.20	0.37	0.50	4	11.4	0.60	0.53	1.13
RG2	C	X	0.19	0.37	0.50	4	11.4	0.61	X	X
RG4	C	X	0.38	0.50	0.50	4	11.4	0.81	1.00	0.81
LB1	C	X	0.21	0.43	0.50	4	11.4	0.64	0.55	1.16
LB4	C	X	0.22	0.50	0.50	4	11.4	0.64	0.42	1.52

***Soil**: S = sand, SdC = sandy clay, SC = silty clay, C = clay; **Groundwater**: X = not observed, B = touching bottom of pipe, -400 = observed 400 mm below bottom of pipe.

For data set 1, S_w predicted by the model was very close to the value determined in field observations. This has helped confirm that the field determined moisture (and degree of saturation, S_w) at pipe depth that represents a good approximation of the long-term average value. For sites DU2 and BE2 the model-predicted result was lower than the field result. This was expected because the model does not account for the influence of a groundwater table, and a groundwater table was observed at these sites. The close proximity of the ground water table at these sites may explain why the field measured saturation was higher than the model predicted saturation.

The model was also used to check field determined S_w for data set 2. With the exception of site LB4, the model predicted long-term average saturation values that closely matched the one-time field measured values. Therefore the one-time field measured values of saturation were considered to closely represent the actual long-term values. The difference observed between the model estimate and field determined values of S_w for site LB4 may be related to the shallow burial depth (less than 400 mm) of the pipe at this site. At shallow depths the moisture content varies more over time (than at deeper depths), and possibly the site was inspected during a dry period when the soil moisture was lower than the long-term average. The grey highlighted values in Table 3 were considered to be the best estimates of long-term S_w for use in the corrosion model calibration in the following sections.

6. CORROSION VERSUS TIME BEHAVIOUR

Figure 4 shows a plot of the maximum pit depth versus exposure time at all of the condition assessment sites. The data is grouped into the degree of saturation (determined in the previous section) ranges as shown. Lower corrosion was observed at drier sites (see BS1), as was expected. The deepest pits were observed at the wetter sites; however at the wettest and saturated sites (BS2 and RG4) the corrosion was lower. This was also expected. It is likely that WS1 also fits in with the saturated sites. Note that the degree of saturation value determined by the model in the previous section for MW3 was likely a lower bound value due to the proximity of the water table at this site. For this reason MW3 would probably actually be in the next range (S_w = 0.51-0.75), which appears consistent with the other results.

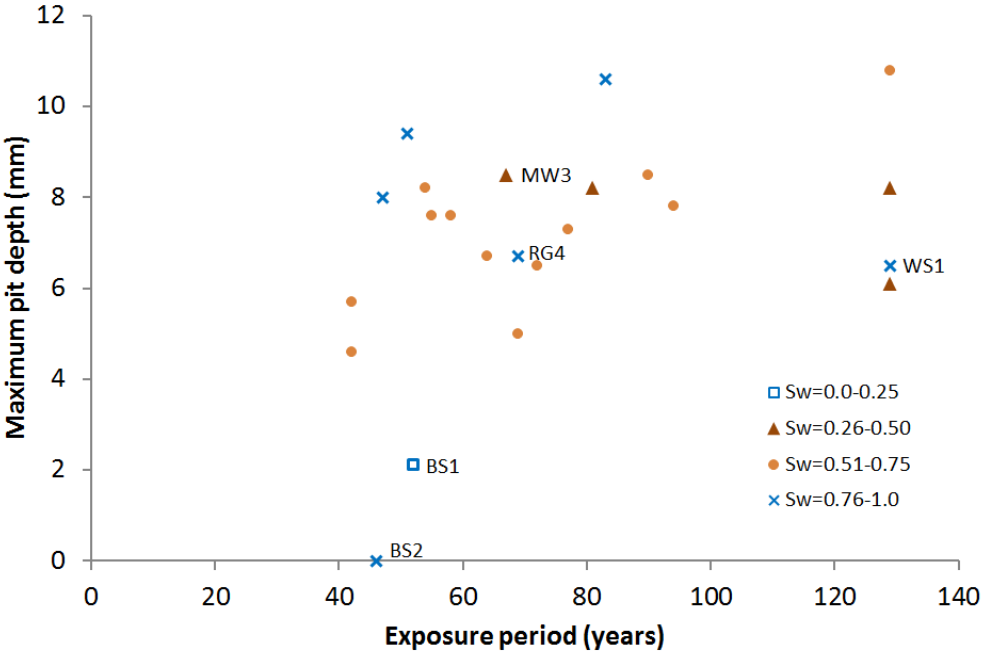

Figure 4 Maximum pit depths versus exposure period for all condition assessment sites. (Names of sites discussed in the text are labelled in the figure)

7. CORROSION MODEL CALIBRATION RESULTS

From the condition assessment data sets there was enough data to calibrate models for three different ranges of degree of saturation: S_w = 0.51-0.60; S_w = 0.61-0.70; S_w = 0.71-0.80. A linear trend line was fitted to each set of data; this trend line represents the long-term maximum pit depth vs time relationship for the given S_w range. Short term data from Romanoff (1957) was also used where available. The model calibrations are shown in Figures 5-7. Point WS1 was left out of the regression analysis because it was considered to belong to the saturated case (see previous section). These calibrations represent an improvement over the preliminary calibrations in Petersen et al. (2013) because more data was used to calibrate the models, plus there was more confidence in the estimated value of the long-term average degree of saturation.

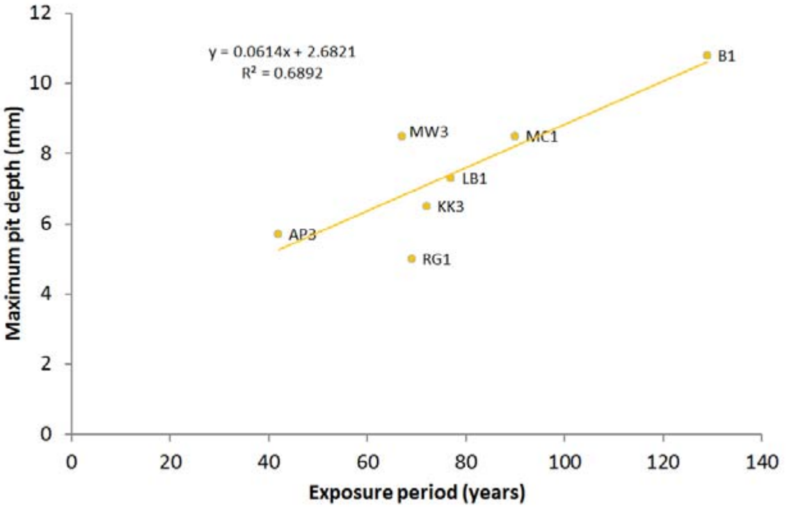

Figure 5 Calibration of long-term pit depth vs time model to data from S_w = 0.51-0.60 group

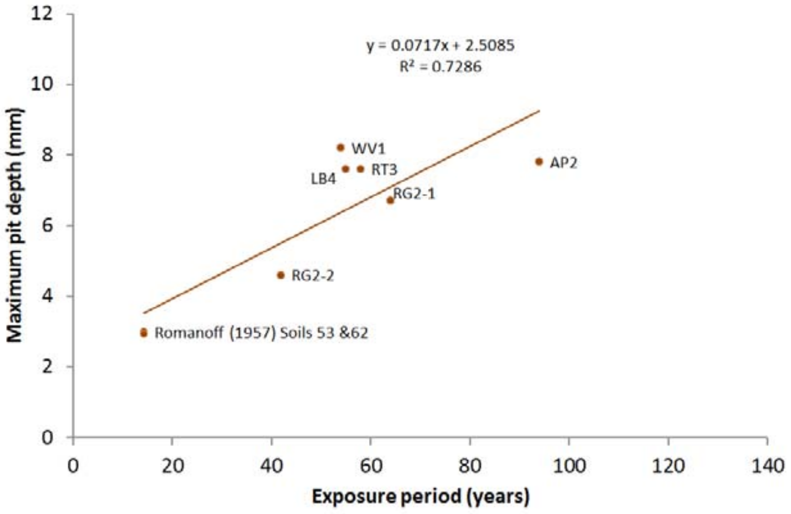

Figure 6 Calibration of long-term pit depth vs time model to data from S_w = 0.61-0.70 group

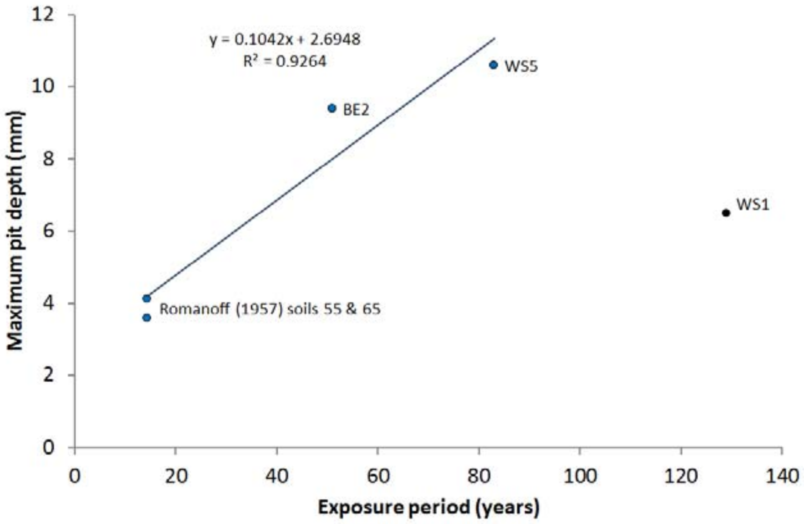

Figure 7 Calibration of long-term pit depth vs time model to data from S_w = 0.71-0.80 group

8. CONCLUSIONS

A climate soil moisture model was used to estimate the long-term average soil moisture content at cast iron pipe condition assessment sites. This information, along with information on exposure time and maximum pit depth was used to calibrate models for the prediction of maximum pit depth versus time for pipes buried in native soil backfill environments, as a function of degree of saturation. The following conclusions were drawn from the study:

1. Predictions of long-term soil moisture content from the proposed climate-soil moisture model match actual field data very closely. Therefore this model can be used to estimate long-term average moisture contents at pipeline condition assessment sites (where the pipe is above the water table).
2. The moisture content determined at pipe depth during the time of inspection was very close to the long-term average moisture content simulated using the verified climate-soil moisture model. Therefore moisture contents determined at pipe depth during the time of inspection represent a reasonable approximation of the long-term soil moisture content. Note that this only applies for clay soils.
3. The calibration for model parameters is for cast iron pipes buried at standard depths in relatively homogeneous, low-permeability, soils with degrees of saturation ranges equal to 0.51-0.60, 0.61-0.70, and 0.71-0.80.
4. This work resulted in an improved model (compared with the model developed previously) because more data was used to calibrate the models, plus there was more confidence in the estimated value of the long-term average degree of saturation.

9. ACKNOWLEDGEMENTS

The authors thank the staff of Hunter Water for their assistance during the planning and subsequent fieldwork components of this project. The authors also thank Matthew Dafter of Hunter Water Australia for supplying his notes from condition assessments on Hunter Water pipes collected as a part of work for his thesis.

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.

10. REFERENCES

Bureau of Meteorology (2014) Bureau of Meteorology, Melbourne, Australia, viewed October-November 2013, http://www. bom.gov.au

Clapp RB and Hornberger GM (1978) Empirical Equations for Some Soil Hydraulic Properties, Water Resources Research 14(4) 601-604.

Diepen CA van, Rappoldt C, Wolf J, Keulen H van (1988) Crop growth simulation model WOFOST. Documentation version 4.1. Centre for World Food Studies, Wageningen, The Netherlands.

Doorenbos J, Kassam AH, Bentvelder C, Uittenbogaard G (1978) Yield response to water. U.N. Economic Commission West Asia, Rome, Italy.

Greve P, Lejeune Q, Wilhelm M (2013) SimBuck: A Simple Bucket Model for Soil Moisture Simulation, Institute for Atmospheric and Climate Science, viewed 10 April 2014, http://www.iac.ethz.ch/edu/courses/master/modules/land-climate-interactions/HS2013/LCI13-EX1-sheet

Kodikara J, Rajeev P, Chan D, Gallage, C (2014) Soil moisture monitoring at the field scale using neutron probe, Canadian Geotechnical Journal 51 332-345.

Petersen RB and Melchers RE (2012) Long-term corrosion of cast iron cement lined pipes, (In) Corrosion and Prevention, Nov 11-14, Melbourne, Australia.

Petersen RB, Dafter M, and Melchers RE (2013) Modelling the long-term corrosion of cast iron pipes, (In) Corrosion and Prevention, Nov 10-13, Brisbane, Australia.

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

Zotarelli L, Dukes MD, Romero CC, Migliaccio KW, Morgan KT (2013) Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method), Agricultural and Biological Engineering Department., Florida Cooperative Extension Service, Institute of Food and Ag Sciences, Univ. of Florida.

11. 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 and a PhD from the University of Cambridge, UK. He is a Fellow of the Australian Academy of Technological Sciences and Engineering. Currently he is one of two Visiting Scientists, European Economic Community Marie Curie BIOCOR research program (2010-13). He was awarded the Marshall Fordham prize (ACA) in 1999, 2002 and 2007, 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 2009 ACA Corrosion Medal and the 2012 Jin S Chung Award (International Society of Offshore and Polar Engineers). His research interests include structural reliability and marine corrosion.