PREDICTING THE CORROSION OF CAST IRON PIPES

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ABSTRACT

Time of wetness, microbiologically influenced corrosion (MIC) governed by availability of nitrate in the soil water and soil water chlorides are demonstrated as the primary influences for long-term external corrosion of cast iron water pipes in soils. The critical influencing parameters are quantified for a near-homogeneous cohort of exhumed pipes up to 129 years old. They show good numerical correlation with detailed measurements of exterior corrosion penetration for the corresponding pipes. The need for adequate measurement of corrosion penetration and the parameters for MIC, the need for adequate estimation of time of wetness, and the potential influences of physical damage and poor quality backfill are discussed.

INTRODUCTION

The deterioration of large diameter cast iron water mains is of interest to the water industry. Deterioration of these pipes is mainly the result of corrosion on the external surface of the pipe in contact with soil. Because of the high cost of replacement and maintenance of these pipes asset managers usually are interested in extending the life of these buried assets as long as possible. Increasingly asset managers are moving towards using mathematical and statistical models to predict the current condition of the pipe and also the likely future corrosion rates. This paper outlines a novel approach adopted by researchers at The University of Newcastle to predict the long-term corrosion progression on the external surface of a buried cast iron water pipe.

As shown repeatedly in the literature, the models currently available for the prediction of corrosion in soils under long-term exposure conditions are inadequate (Rossum 1969, Rajani et al. 2000, Alamilla et al. 2009, among others). Recently all these models have been shown to be inconsistent with the extensive data reported by the US National Bureau of Standards (Romanoff 1957). To improve on this situation, the long-term behaviour of ferrous materials in soils was reassessed and the model shown in Figure 1 proposed (Petersen and Melchers 2016). This model is consistent with corrosion theory and also with models previously developed for long-term corrosion of steels under immersion and atmospheric conditions (Melchers 2013). The proposed model fits with the notion, also suggested by Tomashov (1966), that active corrosion in soils is wet corrosion and therefore should have similarities with corrosion under immersion and wet atmospheric conditions.

Typically in-service cast iron pipes are quite old, with ages ranging between 35 and 135 years old. For exposure periods as long as these (15 years and above), only the trend in phase 4 of the model (Figure 1) is of interest. As a first approximation, this can be represented by a linear function as shown in Figure 1, with this function being strongly related to the environment surrounding the pipe.

Important factors for long-term corrosion include the degree of wetness of the pipe surface over time, the influence of microbiologically induced corrosion (MIC) which is governed by the availability of critical nutrients, and the presence of chlorides, phosphates and carbonates (Petersen and Melchers 2012). These are the parameters that were primarily considered in this work, with nitrate concentration being considered to be the governing factor for MIC. Long-term corrosion in soils also may be influenced by other factors such as pH, soil temperature, permeability, resistivity, and physical damage to the pipe (Petersen and Melchers 2012).

Existing data sets for corrosion losses and corrosion penetration and associated reported soil parameters were found to be inadequate for model calibration since the data did not include parameters that are important to underground corrosion, including those required to estimate a time of wetness of the metal surface, nutrients for microbiological corrosion, and the presence of inhibitors such as phosphate. New data was sought for calibration of the model (Figure 1) and these were collected in a set of novel and very comprehensive field data collection studies.

The next section provides an outline of the field work conducted to collect new data for model calibration. This is followed by an overview of the analysis of this data and the derivation of relationships between corrosion penetration and influencing factors including time of wetness, nitrates for MIC, and chlorides. This is then followed

by discussions on estimating the time of wetness, and the potential effects of physical damage, poor quality backfill and material imperfections. This paper provides a general overview of the work conducted. For a detailed report of this work refer to Petersen et al. (2016).

FIELD WORK

Data for model calibration was collected in a set of field investigations on actual trunk main water pipes. In total 37 pipes were examined from different sites in three general locations: Newcastle (20), Sydney (15) and Perth (2). Investigation sites were made available through scheduled routine inspections, water main bursts and the abandonment of one pipeline. At each site the pipe was exhumed, examined and the soil sampled. For this a standard data collection protocol was developed. It specifically included sampling for nutrients known to be involved in microbiologically influenced corrosion, including nitrates, phosphates, sulphates, and total organic carbon (Petersen et al. 2013).

To inspect each pipe the pipe was first grit blasted to reveal the corroded surface. The majority of pipes were then scanned with a handheld 3D laser scanner (Creaform). The data from which could be used to generate a 3D computer model of the exterior surface of the pipe, and from which could be interrogated to determine maximum pit depths. Some pipes were not laser scanned, and in these cases pit depth gauges were used to determine maximum pit depths.

The main results of the investigations are summarised in Table 1. As can be seen, the pipes range from some of the oldest pipes in the water networks (129 years) to much more modern cast iron pipes. The soils were classified mainly as inorganic clays and sands with some classified as loam. All the pipe samples were for pipelines buried under grass easements, except sample 6 (under a gravel access road) and samples 26, 36 and 37 (under paved roads).

At most sites the trenches were backfilled with native soil (Table 1). Sites 1, 4 and 8 showed some visual evidence of the backfill being in part imported sand. Groundwater either was not observed or appeared to reach no higher than half-way up the pipe. This was the case for all sites examined. Additional information on the field work method and results are included in Petersen et al. (2016).

ANALYSIS

Corrosion penetrations
The pit depth data obtained from analysis of the 3D scanning data was used for extreme value analysis. Much of the pit data was found to be consistent with

a Gumbel extreme value distribution, but in most cases there were a few pits measured to have much greater depth. These pits were thought to be material imperfections in the cast iron, rather than corrosion pits. They were considered as outliers. The remaining deep pits typically were bunched together by depth and were taken as a cohort representing the best estimate of maximum corrosion depth, p_0. In the few cases where scanning was not carried out the maximum measured pit depth was used. The values of maximum corrosion penetration determined this way are shown in column 10 in Table 1, and are also shown in Figure 2 against exposure period t. Although there is a gradual upward trend, as would be expected, it is clear that there is very large scatter in the data.

Homogeneous population
For the analysis of the effect of various parameters on corrosion it is necessary to have a homogeneous population. An approximation to a homogeneous set can be obtained by elimating obvious outliers. Examination of the corrosion penetrations shown in Figure 2 suggests that the corrosion values at sites 1, 11, 24, 25, 29 and 34 could be outliers, resulting from influences or conditions not consistent with the rest of the data. Detailed review of the records for each of the sites showed that there were indeed unusual conditions associated with each. Sites 1 and 11 had poor backfill, which from practical experience has been known to influence corrosion. Site 24 was located near a grassed storm water detention basin, and site 25 was located immediately adjacent to a sub-surface storm water drain. Field inspection of sites 29 and 34 showed these sites to be poorly drained. Sites 1 and 11 were disregarded in the following analysis. However, comments about their potential importance are given in the Discussion. The possibility of prolonged periods of wetness at sites 24, 25, 29 and 34 was noted for the following analysis.

Comparison between data – adjustment to a standard penetration-time curve
To allow comparison between the sites and the development of a consistent trend with time, the following adjustments were made to the data. Firstly, to account for variation in pipe wetness between sites, a percentage time of wetness of the pipe surface was estimated and used to determine the total time that the pipe was wet enough for corrosion to occur. This time, termed time of wetness t_w, was used instead of pipe burial time. Secondly, corrosion penetrations p_0 remaining after removing the outliers were adjusted to obtain penetration values for zero nitrates and zero chlorides as described below.

In the following analysis the influence of various other factors was ignored. These include organic carbon and soil water sulphates and phosphates,

which were assumed adequate to support microbiological activity. Because of similar (historical) water industry practices and controls, it was assumed that the conditions for pipe bedding and for backfill were similar. Soil compaction and therefore permeability was considered to have little variation across the sites. Similarly, because of the relatively close proximity of the majority of sites it was assumed that soil temperatures were similar at all sites.

Phosphates are known to act as corrosion inhibitors (Roberge 2008). As a corrosion inhibitor its effect is likely to have been small since the concentrations are low. Carbonates can also act as corrosion inhibitors (Jack and Wilmott 2011), but in the present study the values of soil pH (Table 1) do not support any of the soils being calcareous. The effect of phosphates and carbonates were thus ignored for this study.

Adjustment for time of wetness

Similar to atmospheric corrosion, corrosion in a soil is expected to progress only by an appreciable amount when there is a sufficient level of moisture present at the corroding surface. Also, it is expected that this surface wetness is related to the amount of water held in and moving through the surrounding soil. Studies by Gupta and Gupta (1979) on sandy and loamy soils indicate that for low soil moisture contents there is no corrosion, and that there is a sharp rise in corrosion levels as the soil moisture content reaches a critical point. They determined this critical point to be when the soil moisture was at 65 % of the water holding capacity of the soil. It follows that at this point there is sufficient water available at the metal surface for significant corrosion.

Based on the above ideas, a 'time of wetness' can be estimated by counting the time the soil moisture is above this critical level. For the purposes of the present study a first estimate of the time of wetness was determined using a mathematical model. The model produces an estimate of soil moisture variation over time by applying a water volume balance calculation over a volume of soil. Water enters the soil via rainfall and is lost through drainage and evapotranspiration (Petersen and Melchers 2014).

For each site soil moisture was calculated daily, over a year, using rainfall and climate data collected in 2001 from a nominal site in the Hunter Valley. The climate data was sourced from the Bureau of Meteorology website (Bureau of Meteorology website, 2014). It was assumed for this initial analysis that the climates would be relatively similar across all sites in the study and for all periods of exposure.

The number of days in which the soil moisture was greater than 65 % of the soil's water holding

capacity was determined and divided by 365 to calculate the percentage 'time of wetness' for that year. This value is given in Table 1 (column 6). For some sites this value was adjusted to take into account external factors which could change soil moisture for periods of time (and/or that were not considered in the simple mathematical model). For example, for Sites 24 and 25, the percentage time of wetness was increased by 30 to account for the presence of a drain and storm water detention basin, respectively.

The percentage time of wetness, calculated over a year of rainfall (Table 1, column 6), was then multiplied by the exposure period t to determine the time of wetness t_w over the whole life of the pipe.

The observed corrosion penetrations p_0 are shown in Figure 3 against time of wetness t_w. Evidently, a much clearer trend in the data (compared to Figure 2) is seen. Also, the scatter in the data is reduced considerably.

Adjustment for nitrates (DIN)

Since soil corrosion can be considered as wet corrosion (Tomashov 1966), the effect of DIN for MIC in soils can be assumed to be similar to that in sea- and freshwaters. It was assumed that oxygen has sufficient access into the soil mass to oxidize any nitrites or ammonia in the soil to nitrates. In this case DIN concentration is equivalent to the concentration of nitrates (N). It was assumed also that sufficient (total) organic carbon (TOC), inorganic sulphates and phosphates in the soil were available to render DIN (i.e. nitrates) the limiting nutrient for MIC in soils.

The nitrate adjustment used here is based on the influence of dissolved inorganic nitrogen (DIN) on MIC of structural steel immersed in seawater (Melchers 2014). The results from Melchers (2014) were adapted to suit soil conditions to develop a first estimate for the relationship between the increase in depth Δp_{MIC} of the deepest penetration cohort as a result of MIC fostered by soil nitrates N (mg N/kg). With some additional calibration this relationship was empirically determined as:

$$\Delta p_{MIC} = 0.5N \qquad (1)$$

Details of this derivation are in Petersen et al. (2016).

The greatest influence of MIC is during Phase 3 of the corrosion process (Figure 1) (Melchers 2014). It was therefore assumed that the adjustment in Equation (1) only applied to sites where the time of wetness t_w was beyond this point. After some experimentation with the current data set, it appeared that the time of wetness, after which nitrates cause an increase in depth of the deepest pit, is equal to approximately 20 years. The

adjustment was thus applied to the corrosion penetrations with a t_w >20 years, giving the results plotted in Figure 4. In general the scatter is less than in Figure 3, with site 24 being adjusted the most.

Adjustment for chloride concentration
Empirical observations of pitting corrosion (for up to 16 years) show corrosion is more severe in seawater compared with fresh water of similar pH (Southwell and Alexander 1970). Data from these observations were used to make a first-order estimate for the effect of chlorides on corrosion penetration of cast iron in saline soils, noting also the similarity of corrosion of ferrous metals in soils (Romanoff 1957, Petersen and Melchers 2012). These results were adapted to suit soil conditions with the following relationship being derived for the influence of soil chloride concentration on maximum penetration:

$$\Delta p_{cl} = 8 \times 10^{-6} \, c_{cl}.t \qquad (2)$$

where c_{Cl} is the local chloride concentration (in mg Cl / kg) in the soil. Details of the derivation are provided in Petersen et al. (2016). Applying this to the data for p_0 for the sites in Table 2 shows immediately that the corrections are very small. The resulting plot of net penetrations versus time of exposure is shown in Figure 5. Mean and percentile trend lines are also shown.

DISCUSSION

Despite the scatter remaining in the adjusted data, the mean and the percentile trends in Figure 5 are all as expected, with maximum penetration increasing with increasing exposure period. When plotted against time of wetness the penetration data could be interpreted as following a bimodal trend with time. The longer term data with a time of wetness greater than 20 years can be represented by a linear trend that does not go through the origin.

Comparing Figures 3, 4 and 5 shows that the main influencing factors are, in order, time of wetness and inorganic nitrate. The former is important both for abiotic and for biotic corrosion and the latter being the critical nutrient for MIC, if other nutrients such as organic carbon, sulphates, and phosphates are sufficiently available. Neither of these parameters has been considered explicitly in any previous analysis of corrosion of ferrous metals in soils.

The current work has shown the important influence of 'time of wetness' for soil corrosion. Obviously for any future analysis and prediction of corrosion depths of metals buried in a soil this parameter needs to be estimated with reasonable accuracy. For the present work a simple mathematical model for soil moisture with rainfall inputs, and with

adjustments to account for local site factors, was found to be adequate. Nevertheless, there remains room for improvement of the models and methods used. In particular, the estimation of time of wetness relied herein on having an estimate of a critical moisture content above which the metal surface was sufficently wet for corrosion to be significant. This value has been determined for sands, and loams, but not for clays. Also it remains to be seen what exactly is the relationship between soil moisture and the corrosion in a clay soil. These matters require further investigation. Also, the present investigation has shown that water utilities might take note of local conditions that could elevate the time of wetness at the pipe-soil interface. The present results suggest that knowledge of such local conditions is needed for estimation of a time of wetness.

Whereas the variation of moisture was estimated using the modelling described above, the values of the other soil parameters, such as nitrates and chlorides, were only determined from soil samples collected at a single point in time. Implicitly it was assumed that these are a sufficiently good representation of their long-term average value, that is, over the corresponding total period of exposure. In reality this is unlikely to be true and some (relatively small) variation can be expected daily, seasonally and yearly.

Assessment of outliers identified the potential for increased corrosion in poor quality backfills. Quantification of the extra corrosion caused by damage from hard backfill and the localized corrosion caused by heavy clays in the backfill are currently under further investigation. A lesser issue is the occurrence of material imperfections in cast irons. It has been noted that casting imperfections and defects can be around 1-2 mm in equivalent diameter (Soltani Asadi and Melchers 2015). Further, for prediction of remaining pipe strength or containment capacity, the likely size (area) of corrosion pitting is required. This aspect also is under current study and is being considered using the detailed scanning information obtained for the corroded external surfaces of pipes.

CONCLUSIONS

1. New data for the corrosion of cast iron pipes buried in various soils for up to 129 years are reasonably consistent with a nearly linear long-term trend consistent with phase 4 of the previously proposed bi-modal model,

2. The main factors influencing soil corrosion are, in order, time of wetness of the pipe surface and inorganic nitrate. Chlorides play a relatively minor role. Phosphates and carbonates are considered secondary influences.

3. Expressions are given for the maximum penetration of the cohort of deepest corrosion pits as functions of time of wetness, inorganic nitrate and chlorides, both for mean trend and for the 5, 10, 90 and 95 percentile values.

4. The potential influences of physical damage from poor quality backfill including rocks and clays, material imperfections and the need for improved methods to estimate time of wetness are noted.

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Table 1. Soil parameters and corrosion penetration observed for buried cast iron pipes

	Site	Pipe type [a]	Time (years) [b]	Soil backfill type	Soil pH	Percent Time of wetness	NO3 as N (mg/kg)	Chloride (mg/kg)	PO3 as P (mg/kg)	Maximum corrosion penetration p_0 (mm)
	Column No.	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Set 1									
1	BO2	YS	34	clay	6.5	x	1.0	180	0.7	7
2	RT1	YS	36	sand	5.4	1	0.7	10	18.9	1.7
3	RT2	YS	36	sand	5.3	1	0.3	50	5.9	3.8
4	BE7	YS	43	sand	6.3	1	0.0	30	0.5	1.4
5	MC4	YS	46	clay	8.3	23	0.0	60	2.8	4.7
6	DU2	YS	47	clay	6.0	40	2.5	160	1.2	8
7	BE2	SD	51	clay	5.6	41	0.7	120	0.2	6.5
8	BE5	SD	51	clay	5.7	1	2.1	310	0.1	6
9	MC3	SD	54	clay	7.9	44	0.7	80	0.4	6.4
10	RT3	SD	58	clay	7.3	25	0.2	230	11.1	7.6
11	CE2	SD	71	clay	6.0	x	0.8	30	0.0	12.9
12	KK3	D	72	clay	4.6	41	0.0	10	0.0	6.5
13	MC5	D	74	clay	6.3	18	0.9	190	0.3	5.7
14	WS5	VC	83	clay	5.6	46	0.0	70	1.0	9
15	MC1	VC	90	clay	6.4	25	0.0	600	1.2	8.5
16	WS1	VC	129	clay	5.1	44	0.0	200	0.3	8.5
17	WS2	VC	129	clay	6.3	22	0.7	650	3.1	11.5
18	WS4	VC	129	clay	7.9	16	1.4	180	0.5	8
19	B1	VC	129	clay	5.1	24	1.7	20	0.0	10.5
20	B2	VC	129	clay	5.6	19	1.4	60	0.1	8.5
	Set 2									
21	WMMA08	YS	36	clay	8.4	29	17.8	250	3.2	4.3
22	B. Hills	YS	36	clay	5.7	29	12.3	116	5.2	4.2
23	WMMA01	YS	44	clay	6.6	29	8	133	2.6	3.8
24	WMOH02 Kingswood	YS	45	clay	6.3	60	14.3	866	1.7	14
25	WMOH02 Sth. Pen.	YS	45	clay	7.5	60	3.4	1306	0.8	16
26	WMBX01	SD	59	loam	8.7	10	4.1	13.8	1	4
27	WMSF01	SD	61	loam	5.7	29	60	47	1.9	5.1
	Set 3									
28	T2P1	VC	90	clay	6.0	40	1.5	300	0.7	6
29	T2P3	VC	90	clay/ sand	5.9	100	1.4	450	0.5	20.3
30	T2P4	VC	90	clay	7.7	63	2.3	340	0.5	9.1
31	T3P1	VC	90	clay	7.9	100	3.1	966	0.6	11.4
32	T3P2	VC	90	clay	7.4	38	2.1	245	0.3	7.7
33	T3P3	VC	90	clay	7.5	100	1.5	275	2.25	12.9
34	T3P4	VC	90	clay	7.5	100	1.5	275	2.25	17.2
35	T5P1	VC	90	clay	6.4	44	1.2	50	1	10.4
	Set 4									
36	WC11	VC	81	sand	6.4	1	0.1	10	0.1	4
37	WC22	VC	81	sand	8.2	1	0.2	10	0.2	1.8

[a] Pipe type: YS = Yennora spun; SD = Super deLavaud - Australian Institute of Steel (AIS); D = deLavaud (AIS); VC = Vertically sand cast.
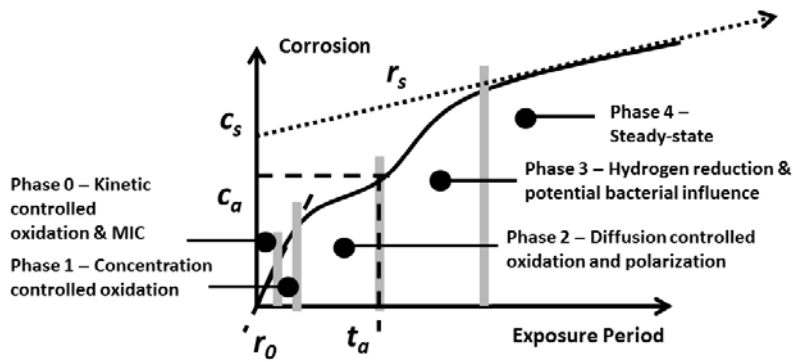[b] Based on pipe installation date.

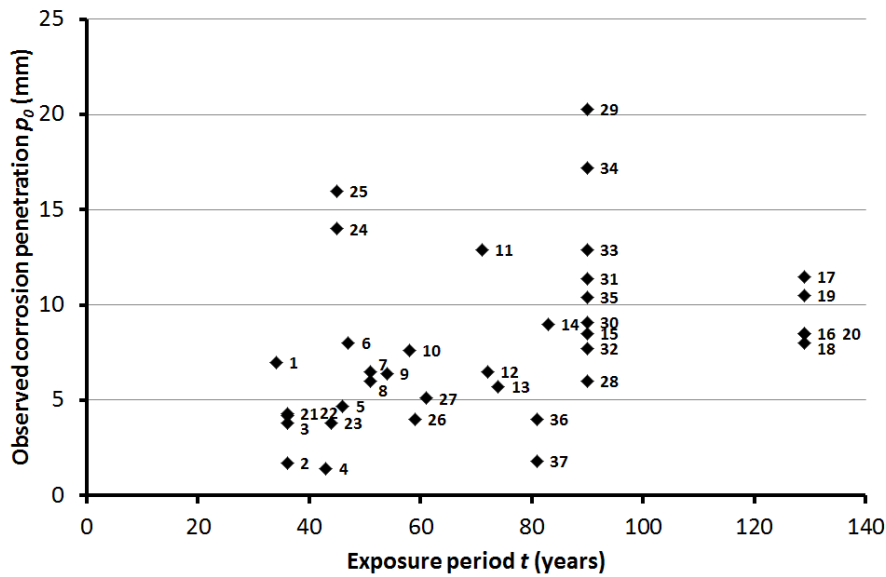Figure 1. Bi-modal model for corrosion loss as a function of exposure period

Figure 2. Observed corrosion penetrations p_0 (column 10, Table 2) versus exposure period t. Note the very large scatter in the data.
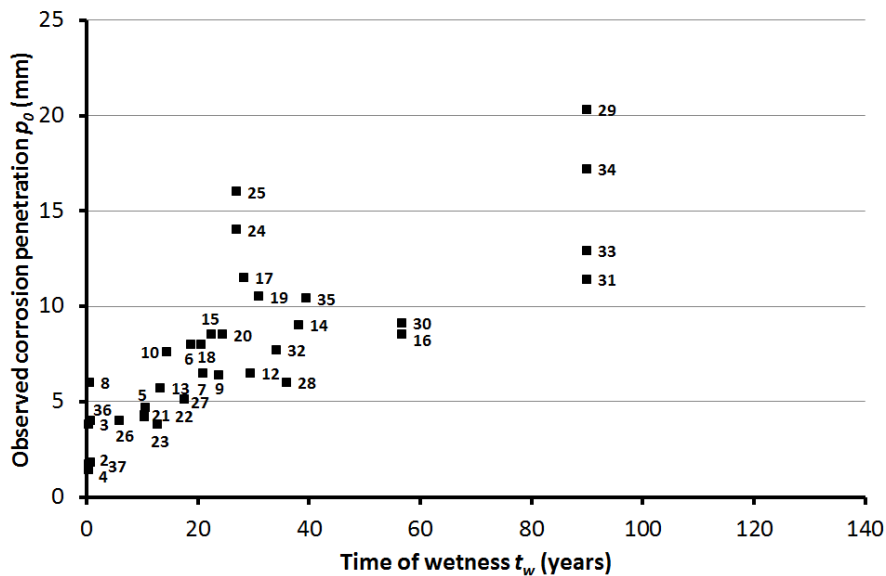

Figure 3 Corrosion penetrations p_0 versus time of wetness t_w. Time of wetness t_w is equal to the percentage time of wetness (column 6, Table 2) multiplied by exposure period t. The scatter in the data is less than in Figure2. Also a much clearer trend has emerged.
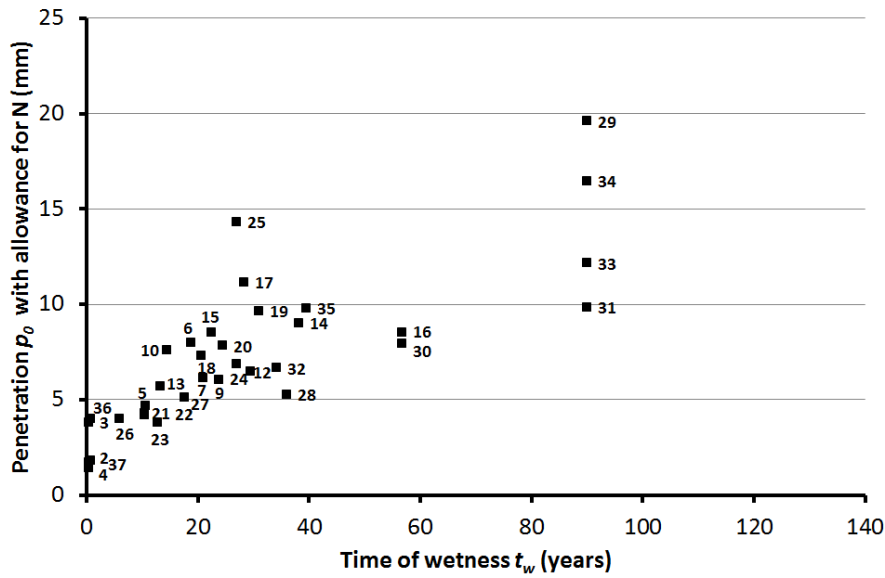
Figure 4.Corrosion penetrations p_0 with allowances for soil nitrate content, versus time of wetness t_w. The scatter is somewhat less than in Figure 3.
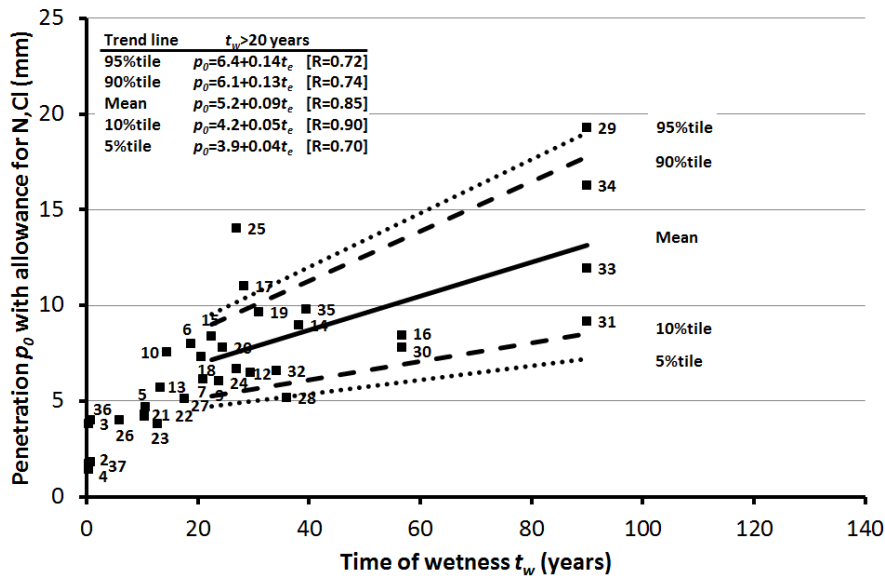

Figure 5.Corrosion penetrations p_0 with allowances for soil nitrate content and soil chloride content versus time of wetness t_w. The scatter in the data is almost the same as in Figure 4. Mean value and percentile trend lines are shown for $t_w>20$ years.