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Extreme value statistics for pitting corrosion of old underground cast iron pipes

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ABSTRACT

Many major city water supply distribution networks consist of buried cast iron pipes. In many cases the pipes are internally cement-lined and the predominant corrosion is by external pitting. This may cause leakage and eventual structural failure. It is conventional to use the Gumbel extreme value distribution to represent the statistics of maximum pits depth and to use it to estimate the probability of pipe wall perforation. Herein data obtained for maximum pit depths for large-sized (1–2 m long) samples of 10 pipes exhumed from different, apparently randomly selected, locations after 34–129 years of service are examined for consistency with the Gumbel probability distribution. This was the case for the deepest pits, but the data for less deep pits show a consistent pattern of departure from the Gumbel distribution. Some extreme pit depth data, inconsistent with the rest are interpreted as possibly caused by material imperfections.

1. Introduction

Cast iron has been used for water supply mains and for distribution systems for many years and for many cities is still the predominant material for existing water distribution systems. It follows that the reliability and in particular the corrosion behaviour of existing cast iron pipes is of considerable interest to water supply authorities. This is the case worldwide. Where the pipes are internally cement lined the most critical corrosion problem is external, usually attributed to the corrosiveness of the surrounding soil. As the pipes age and corrosion continues the pipe failure frequency tends to increase. This causes direct as well as consequential costs. The annual direct cost arising from external corrosion of water mains has been estimated at approximately $5 billion [1]. This, and the increasing need of water utilities to meet licensing and operational requirements, has increased interest in the prediction of the remaining service life of pipes. At the present time, however, the capabilities for estimating or predicting the likely loss of material as a result of corrosion or the depth of the deepest corrosion pits after many years exposure in a soil environment is still limited [2]. This includes consideration of classical measures such as soil electrical conductivity or resistivity, soil moisture content, soil redox potential, pH, and the influence of soil composition, soil permeability and other such properties and also sulphate, chloride, phosphate and nitrate concentrations, individually or in combination [3,4]. One potentially important aspect is that for cast irons the rate of corrosion loss and the growth of maximum pit depths tend to reduce with longer exposure durations [5], a phenomena also observed for cast irons in other exposure environments such as sea and fresh waters and in the atmosphere [6]. Such reduction in corrosion rate and pit depth growth also has been observed for cast irons of various types and for other ferrous materials, in many different soils [7].

Recent papers have reviewed many of these factors and much of what had been proposed previously for the corrosion of ferrous pipes in soils [2,8,9]. This includes the possibility of involvement of microbiologically influenced corrosion of buried objects, first proposed many years ago [10]. In addition, it has been proposed [11] that since corrosion in soils involves the same main influencing factors (oxygen and water) there should be similarities with atmospheric and with immersion corrosion These aspects have been elaborated recently [12] using both the Romanoff data [7] for cast iron and new, independent, field data for external soil corrosion of internally cement lined cast iron water supply pipes exposed for up to 129 years. Some of that new data, in particularly that for pitting of cast iron pipes in soils, provides the basis for the present investigation.

When pipe life is likely to be limited by the depth of corrosion pits, the use statistics and probability theory is appropriate for extrapolation to larger areas and to longer time frames [13–16]. The corrosion literature [17,18] shows that the uncertainty associated with the maximum pit depths can be treated by applying Extreme Value (EV) statistics. Indeed analysis of corrosion pitting using Extreme Value statistics often is claimed to be an arch-typical EV application. This method of analysis attempts to relate the probability of a given pit

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depth being exceeded with the scatter in the data [19].

In the following, a brief review is given of the developments of extreme value theory applied to corrosion pitting, followed by a description of an experimental program involving 10 pipes ranging in age from 34 to 129 years. They were part of a regular inspection program run by Hunter Water (Australia) on pipes that were in-service. They were (and are) selected on the basis of opportunity to inspect and can be considered essentially a random collection of cases. None of the pipes had failed. In each case lengths of 1–2 m of these pipes were exhumed, grit blasted in-situ to remove corrosion products and measured for pit depth. The pit depth results are then interpreted using the Gumbel EV distribution as a starting point. Interpretations of the results are then given and possible implications discussed.

2. Background

One of the first to apply EV statistics to corrosion pitting was Aziz [20] who considered aluminium in fresh water under a variety of exposure conditions. He provided an extensive and insightful discussion of a number of the limitations of using EV analysis, including the issue of the ‘tails’ of the distributions, but despite some reservations, concluded that the Gumbel or the First Extreme Value (EV-1) distribution was the best overall choice for fitting to data for maximum depth pits. This is consistent with the original derivation of the Gumbel EV distribution from extreme value arguments for maxima [19]. Subsequently, Hay [21] employed the Gumbel distribution to analyse maximum pit depth data of buried cast iron pipes. Sheikh et al. [17] showed that maximum pit depths were characterised by extreme value analysis and they proposed a probabilistic model to estimate the time of failure. There are a number of other efforts following essentially the same approach first used by Aziz and there also are extensions, such as the use of the r deepest, rather than just the deepest pit, with $r \ll N$ where N is the number of pits in each sample [22–24]. In some applications it was noted [25] that the data sets showed what appeared to be one or more outliers not consistent with the Gumbel distribution. Often these were dismissed, for undefined reasons. Others such as Katano et al. [26] considered that pit depth data obtained for actual cast iron pipes exposed for long periods in the ground were better represented by distributions such as Weibull and Lognormal, the choice apparently depending on the data set and the length of exposure. Overall they proposed the Lognormal as the best fit for representing uncertainty in maximum pit depth under long-term exposures. They did not publish their data and efforts to obtain it were unsuccessful.

Kleiner et al. [2] analysed data sets for pits observed on pipes exhumed in 4 different North American cities and, that the pit depths fitted a so-called’right-truncated’ Gumbel distribution and considered this fitted the data quite well. For this work the right hand truncation was set by the thickness of the pipe wall, since a pit cannot penetrate beyond it, and the pipes did show perforation. However, unlike earlier investigators and unlike the standard approach used in extreme value texts [27–29], they did not plot their data on a so-called Gumbel plot. Instead they used a conventional cumulative distribution plots and compared with a theoretical curve, following which the probability distribution parameters were selected so as to best approximate the data. Because both data and the curve are non-linear, direct comparison would not easily reveal the sort of inconsistencies already noted earlier for some data sets for pitting of steels [30] and of which Kleiner et al. [2] were clearly aware.

The approach for the analysis in the present paper is to use the theoretical Gumbel EV distribution as the starting-point for interpreting data. As is well-known, the Gumbel EV distribution was derived from first principles as the theoretical distribution for the extremes of maximum values from a population of independent samples [31,32]. As noted above, this EV distribution has been widely applied to pit depths. Properly applied, it provides a means for extrapolating in time and in space, and to do so with sound theoretical support, noting the limitations discussed by Aziz [20]. As also noted above, in cases where the data did not appear not to fit the Gumbel EV distribution closely other distributions have been proposed as more appropriate (for example Katano [26]) but it should be clear that the fitting of such distributions is entirely empirical, and any extrapolation in time or in space without a theoretical justification. This is not the approach to be used here. Instead, where there are departures from Gumbel, the present paper attempts to provide understanding of the possible reasons for such departures.

The next section describes the data from the 10 samples, summarizes the different the soil conditions for each pipe and summarizes the methods used for measuring pit depths and for the extreme value analysis. The following section describes the outcomes of the extreme value analysis for each of the 10 pipe samples. The results are then discussed in detail, including comparisons with previous work for cast iron pipe pit analyses and with extreme value pit depth analyses for other metals and for other exposure environments.

3. Experimental procedure

As noted, regular maintenance practice applied by most Australian water utilities for internally cement lined cast iron water mains involves the selective observation of short (2–3 m) lengths of such pipe, typically by opening up the soil and inspecting the pipe, mainly as a precautionary measure to assess pipe condition and so attempt to prevent pipe failures. In some cases the pipe was removed. Ten such inspections became available from different parts of Hunter Water network. None of these was associated with pipe failure. These inspections and thus the lengths examined were opportunistic, selected by Hunter Water and may therefore be considered as a set of random samples. Table 1 shows the 10 samples coded by location, with pipe details. The physical, pipe manufacture and age details for the pipes were obtained from records held by the water utility. Typical compositions for the pipe types in the present study are shown in Table 2.

All sample pipe lengths were marked for identification and, where removed, also for orientation. In most cases the part of a pipe to become the sample was grit blasted in-situ, with particular attention paid to pitted regions to ensure removal within the pits as well as elsewhere of all graphitized material and corrosion product. The effectiveness of the cleaning process was assessed by careful inspection before a pipe sample was released for further examination. The exposed clean cast iron surface was then scanned using a commercial hand-held laser scanner. In a few cases the pipe section was marked and removed and taken for off-site (commercial) sandblasting prior to laser scanning, again with close inspection of the effectiveness of the cleaning process. In all cases there were some parts of the pipe without evidence of corrosion and which was scanned at the same time to provide a reference surface, preferable around the pipe circumference. The latter is preferred because it is known that cast iron pipes are not perfectly circular. The surface features of the pipes varied considerably (Fig. 1). Fig. 1b shows an exhumed pipe (not part of the present study) with severe pitting and longitudinal cracking causing failure as a result of internal water pressure.

As part of a wider project on long-term corrosion of cast iron water mains, at least one soil sample is taken in the immediate vicinity of each pipe section that was (about to be) exhumed. Where possible the soil sample was taken at mid-pipe height almost immediately adjacent to the pipe. Care was taken to not have samples contaminated by the excavation process, in particular its water content. The information about the environment and the soil properties are given in Table 1, since such information may be useful for other studies. The soil properties were determined at a certified commercial testing laboratory (Hunter Water Australia).

For scanning the exterior surfaces of the pipes, a commercial hand held laser scanner was used. It has a resolution for pit depth of 40 μm