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Estimating the Long-Term Reliability of Steel and Cast Iron Pipelines Subject to Pitting Corrosion

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Abstract: Water-injection, oil production and water-supply pipelines are prone to pitting corrosion that may have a serious effect on their longer-term serviceability and sustainability. Typically, observed pit-depth data are handled for a reliability analysis using an extreme value distribution such as Gumbel. Available data do not always fit such monomodal probability distributions well, particularly in the most extreme pit-depth region, irrespective of the type of pipeline. Examples of this are presented, the reasons for this phenomenon are discussed and a rationale is presented for the otherwise entirely empirical use of the 'domain of attraction' in extreme value applications. This permits a more rational estimation of the probability of pipe-wall perforation, which is necessary for asset management and for system-sustainability decisions.

Keywords: steel; cast iron; pipelines; pitting; reliability; extreme value analysis

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1. Introduction

Pipelines play an important if seldom-recognized role in modern society. They are used as part of offshore and on-land oil and gas production and transportation, drinking-water supply systems and the conveyance of sewage to treatment plants. For these systems, loss of containment of contents by through-wall pitting or fracture under extreme internal pressure are the two most important failure modes. In some cases, a fracture can also result from ground movement. In the present paper, only pitting is considered, limited to the low-alloy steels and also cast irons widely used for these pipe systems. The prime focus is on the variability in the maximum pit depth encountered in the practical applications and, thus, the prediction of the probability of wall perforation. This has implications for asset management and for life extension and, by implication, for sustainability. It also means that probabilistic methods must be used.

Three areas of application are considered. One is the internal pitting corrosion of bare-steel water-injection pipelines, and the other is the internal pitting of crude-oil production pipelines, both as used in the offshore oil and gas industry. In both of these cases, the exposure environment is closely homogeneous, and most of the variability relates to material aspects. The third application is for the external pitting corrosion of (usually unprotected) cast iron drinking-water mains as used extensively in many cities and urban areas world-wide. These pipes are buried in various soils, ranging from sands to heavy clays, and, as will be seen, this has some effect on the variability of pit depth.

The next section gives a summary overview of the structural reliability theory [1] on which any discussion of asset management with uncertainty must be based [2]. This is followed by a brief summary of the Extreme Value theory, followed by three examples of its application. As is described, these show common features. To understand these features, a brief review is necessary of the modern understanding of the pitting-corrosion phenomenon. This is given in the Discussion, couched in phenomenological rather than electrochemical terms, and shows that much of the conventional notion of the progression of pit depth must be revisited. This then opens the way for a discussion of the meaning of the common features noted for the EV trends for the three examples. It also provides a rationale for the commonly used approach in EVA of the 'domain of attraction', thereby providing a logical way for extrapolation of pit depth and the related probability of occurrence. The paper concludes with comments about the practical implications.

2. Reliability Theory for Pipe Perforation

The reliability of a pipeline can be considered a conventional structural-reliability problem, composed of a series system of considerable length but failing when any one of its components fails. It is thus possible to simplify the discussion to the weakest-link scenario [1]. Let this be represented by a stochastic loading-process system, $Q(t)$, and a resistance random variable, $R(t)$, that is, because of corrosion pitting, monotonically decreasing in time. Before defining $Q(t)$ and $R(t)$ in more detail below, it is noted that the joint probability density at any time t of $Q(t)$ and $R(t)$ is denoted $f_{QR}(t)$. Of interest is the probability of failure, $p_f(t)$. It is a function of time t. According to well-established theory, at any time, t, the probability of failure is [1]:

$$p_f \Big| t = \iint_D f_Q(x) \cdot f_R(x) dx \quad (1)$$

where $f_Q(t)$ is the (conditional) probability density function for Q and, similarly, for R at t. The failure domain, D_f, is usually defined through a Limit State function (or performance function):

$$G(\mathbf{X}) = G(R, Q) = R - Q < 0 \quad (2)$$

where $\mathbf{X}$ collects all of the relevant random and other variables. In the present case, it comprises simply Q and R. It is noted that when one or more of the components of $\mathbf{X}$ is time-dependent, $G(\mathbf{X})$ is also time-dependent, which will be the case here.

A set of limit state functions, $G(\mathbf{X})$, may be necessary in general for pipelines, so as to include failure modes such as bursting, bending moment and/or shear-load limitations, crushing, as well as corrosion of the pipe-wall, independently or in various combinations. Here, only the leakage scenario is considered. Specifically, wall perforation through pitting corrosion can be considered a failure event when the depth of the deepest pit (i.e., $d_{\max}(t)$) of all pits that may exist on a pipe wall is greater than the local wall thickness D. The limit state function becomes:

$$G(\mathbf{X}, t) = R(t) - Q(t) < 0 = [D - d_{max}(t)] < 0 \quad (3)$$

The deepest of deepest pit depths, $d_{\max}(t)$, is a random variable for which statistical properties are required to permit it to be used in Equation (1). Being a maximum over many individual pit depths, $d_{\max}(t)$ can be considered in terms of extreme value theory to estimate its statistical properties, using well-established theory and procedures. The details of these need not be considered herein. However, for the common cases in which the uncertainties in wall thickness D are essentially negligible (since pipes are made from high-precision-rolled steel plates or centrifugally cast iron), it is possible to state the probability of pipe-wall perforation by pitting for any time interval t from zero as:

$$p_f(t) = P\,[D - d_{max}(t)] < 0 \quad (4)$$

The question now arises of how to handle measured pit-depth values to determine the probability density function as required to evaluate Equation (1). Since $d_{\max}(t)$ is a maximum value, the most appropriate statistical theory to invoke is the Extreme Value (EV) theory [3]. It has a long history of application for extreme values, such as maxima, and, for pitting corrosion, the 'arch-typical' EV distribution is the Gumbel distribution for maxima, which was apparently first applied to (rather scant) data for pit depth in aluminum [4], but since then has been applied to many other cases of pitting. The Gumbel EV distribution and other extreme value distributions (e.g., Frechet, Weibull and Generalized [5]) all have long 'tails' in the region of interest. The original three EV distributions (Gumbel, Frechet and Weibull) can each be derived analytically from first principles with some reasonable assumptions, including the important assumption that the observations used as data are statistically independent. This last assumption is often overlooked, but as will be seen further below, is critical in understanding any results from the application of the EV distributions. Fortunately, statistical independence can be assumed asymptotically in certain circumstances [6]. It is noted, in passing, that the Generalized Extreme Value distribution, often used as a last resort when data do not fit the other monomodal distributions, is entirely empirical, with no theoretical justification [5]. It also requires more data for calibration [7].

The usual approach for determining whether data are consistent with a Gumbel EV distribution is to plot the data on a so-called Gumbel plot. It is a plot of the cumulative distribution function for Gumbel, with the vertical axis distorted in such a way that if the data are truly Gumbel-distributed, the data fall on a straight line with an upwards slope. The slope of that line is a measure of the scatter in the data or, equivalently, the variance in the data. The vertical axis of the Gumbel plot is usually defined in terms of the standardized Gumbel variable w, defined as $w = (x - u)\alpha$, where x is the maximum pit depth having a cumulative distribution function (CDF), $F_x(x)$, and a probability density function (PDF), $f_X(x)$, each defined by:

$$F_X\ (x) = F_W\ [(x - u)\alpha] \text{ with } F_W\ (w) = \exp\ (-e^{-w}) \tag{5}$$

$$f_X\ (x) = \alpha\, f_W\ [(x - u)\ \alpha] \tag{6}$$

where u and α, respectively, are known as the 'mode' and 'slope' of the Gumbel distribution, related to the mean, μ_X, and standard deviation, σ_X, of the distribution through:

$$\mu_X = u + 1.1396/\alpha \tag{7}$$

$$\sigma_X = 0.40825\ \pi/\alpha \tag{8}$$

To make this operational, it is necessary to assign a value of the cumulative distribution (i.e., a probability) to each data point, i, in the data set $1, \ldots, n$. The simplest approach is the so-called 'rank-order' method [8], with:

$$F_X(x_i) = P_i\ (X < x_i) = i/(n+1) \tag{9}$$

This provides an unbiased estimator for the cumulative probability for each value of the random variable $X = x_i$. The values of the pit depths, x_i, are then plotted against the corresponding cumulative probability $F_X(x_i)$. In the examples that follow, the left vertical axis is given in terms of the standardized Gumbel parameter, w, and the right vertical axis shows the probability, ϕ, of a pit depth less than the given value.

3. Examples

3.1. Water-Injection Pipelines

For many oil (or gas) wells reaching the end of their most productive phase, it has become common practice to try to drive the remaining oil out of the well by injecting water of some type at high pressure into the well [9]. For this, steel pipelines are commonly employed, not protected on the inside for economic reasons [10]. They may be many kilometers in length and are typically 200–300 mm in diameter, operating at a very high pressure (typically 200 bar) [11]. The injection water may be seawater, produced water (that extracted from crude oil) or aquifer or other water. Thus, the composition of the water can vary considerably. The water is passed through filters to remove sand and other particulates before injection. Moreover, to try to reduce internal corrosion, the water is nominally de-gassed to 20 ppb of oxygen. In some cases, oxygen scavengers, scale inhibitors and corrosion inhibitors are added. It is also not uncommon to 'pig' the pipelines to try to remove as much as possible of the scale and deposits that tend to form on the pipe walls, despite the often-high water velocity employed. One reason for these deposits (that also enter any pitting corrosion) is that the water is also injected with nitrates [12]. These are added to assist the nitrate-reducing bacteria to out-compete the sulfate-reducing bacteria in the oil, as the latter are responsible for high H_2S concentrations in the recovered oil, an undesirable characteristic. Relatively recently, it has become clear that the added nitrates are also responsible for increased corrosion within the steel pipes, owing to the nitrates being a critical nutrient for the bacterial metabolism that fosters microbiologically influenced corrosion (MIC) [13,14]. Finally, monitoring of the condition of the steel pipelines is usually conducted best using 'intelligent' pigging. This involves Magnetic Flux sensors scanning the surface of the interior of the steel pipes [15]. From results obtained in this way, estimates can be made of the corrosion pit depths and the sizes of the pits, using the proprietary software provided by pigging contractors. The intelligent pigging runs provide a large amount of data for pit depths and can be used directly to obtain Gumbel plots [3,16]. One example is shown in Figure 1.

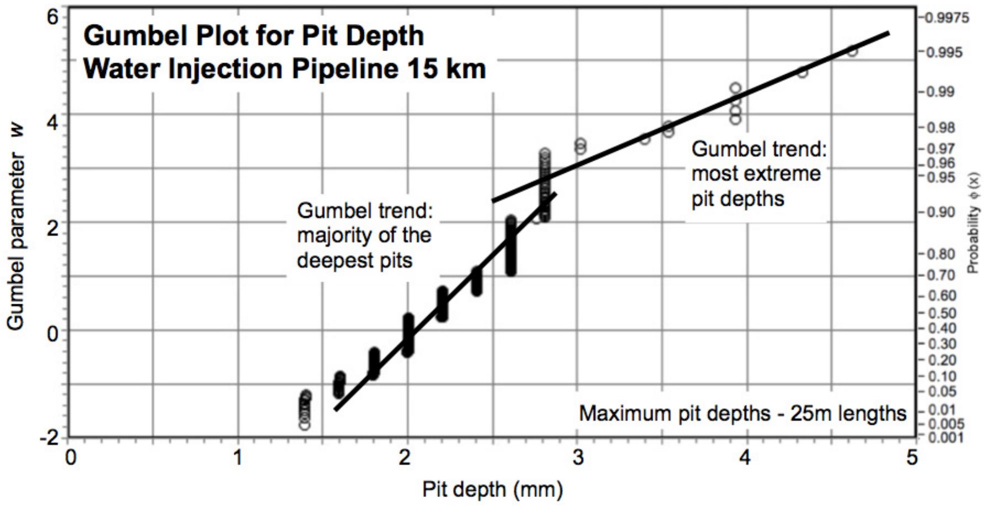

Figure 1. Example of a Gumbel plot for a water-injection pipeline that had been in operation for 10 years. The pit depths on the horizontal axis are those observed, one for each 25 m length of pipe. There are 600 maximum pit depth data points, with 11 or more forming the trend for the overall extremes.

The plot in Figure 1 shows very clearly that all of the data, overall, do not fit a straight line as would be expected if the data were truly Gumbel-distributed. It should be evident that changing the plot to a Frechet or a Weibull (or a Generalized EV) plot, or, indeed, to any other monomodal distribution (e.g., Normal or Lognormal) will only change the scale but not the discontinuous nature of the data trend. Note the extreme-right trend in the data in Figure 1.

3.2. Oil Production Pipelines

Oil production pipelines are not immune to corrosion, owing to the presence of CO_2 and/or H_2S and, in particular, the presence of water in the crude oil. The so-called 'water-cut' can vary widely but, even for relatively 'dry' oils, can be 10% by weight. Since free oxygen does not occur in produced oil, any corrosion must occur under anaerobic conditions, but a good understanding of the mechanisms involved, particularly those responsible for long-term pitting, remains somewhat elusive [17–19], as do the effects of deposition of solids under low-flow or occasional stagnant conditions and that of occasional shutdown periods [20]. The latter may be important as most corrosion has been observed along the bottom of the pipelines. This has also been observed for water-injection pipelines [11], for which periodic deposition during flow shut-downs has been implicated in severe (under-deposit) corrosion [21].

Monitoring of production pipelines is carried out in a similar manner to that of water-injection pipelines, using intelligent pigs. However, there is little in the way of publicly accessible pigging data—some data that became available were analyzed in a manner similar to the pit depth data of water-injection pipelines. The result is shown in the Gumbel plot in Figure 2 for a 15 km long steel pipeline that had been in service for 10 years. It is clear that the data can be interpreted as having several linear (i.e., Gumbel) trends, indicating a piecewise or multi-modal Gumbel distribution. The data for the deepest pits show the right-hand trend with a low slope (i.e., a low value of α in (8)), indicating a high standard deviation. Here, too, the maximum-value pit depths are for each of the 25 m lengths of the pipeline.

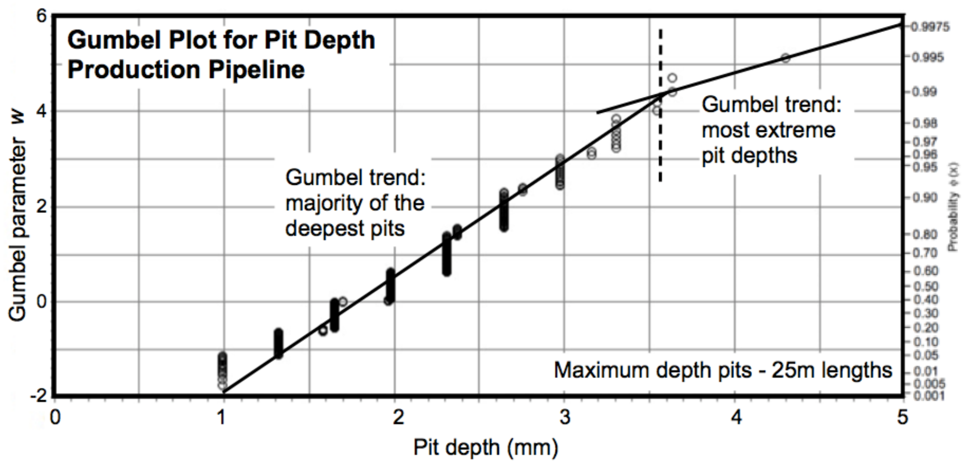

Figure 2. Maximum pit-depth data, plotted on a Gumbel plot for an oil production pipeline after 10 years of exposure (data source confidential).

3.3. Water-Supply Pipelines

For many large cities, a large part of the reticulation system for drinking-water distribution consists of cast-iron or ductile-cast-iron pipes, internally cement-lined to prevent drinking water from being contaminated by corrosion of the inside of the pipes. Such pipes have been in use for many years, since at least the mid−1800s, particularly in Europe [22]. They may fail by fracture (over-pressure, soil movement) but of increasing concern is perforation by pitting corrosion from the outside (soil-side) inwards. Prediction of the time to wall perforation from corrosion pitting is and remains a major issue for water utilities and others responsible for a reliable water supply [23].

Many years ago, it was noted that pipes buried in clay soils showed much shorter durations (50 years) before they failed by leakage and corrosion. However, pipes buried in sands consistently lasted much longer, in many cases for more than 100 years. The reasons for these differences have been subjected to investigations over many decades. Only recently has it become clear, from detailed studies of actual pipes (as distinct from laboratory or artificial field studies), that intimate compaction of soil all around the pipe is critical in corrosion initiation and its severity and that this occurs largely by pitting corrosion [24]. A major research program, funded by various water utilities to develop tools for the prediction of corrosion of water pipes, led to many pipes being exhumed to observe their buried condition. After exhumation, they were grit blasted to remove rust products and they were then subjected to pit depth measurement. One of the major steps forward in the ability to develop a better understanding of the pitting process was the relatively recent availability of digital 3D scanning equipment (e.g., Creaform Exascan®) that permits the development of digital images of the corroded surfaces but also have software (e.g., VXelements® and Pipecheck®) to extract pit depths—many hundreds of them. Using the same approach as for the water-injection pipelines allowed the example Gumbel plot shown in Figure 3 to be obtained. Many other examples are available, though some are perhaps not as well developed in terms of extreme pit depth as the case shown in Figure 3.

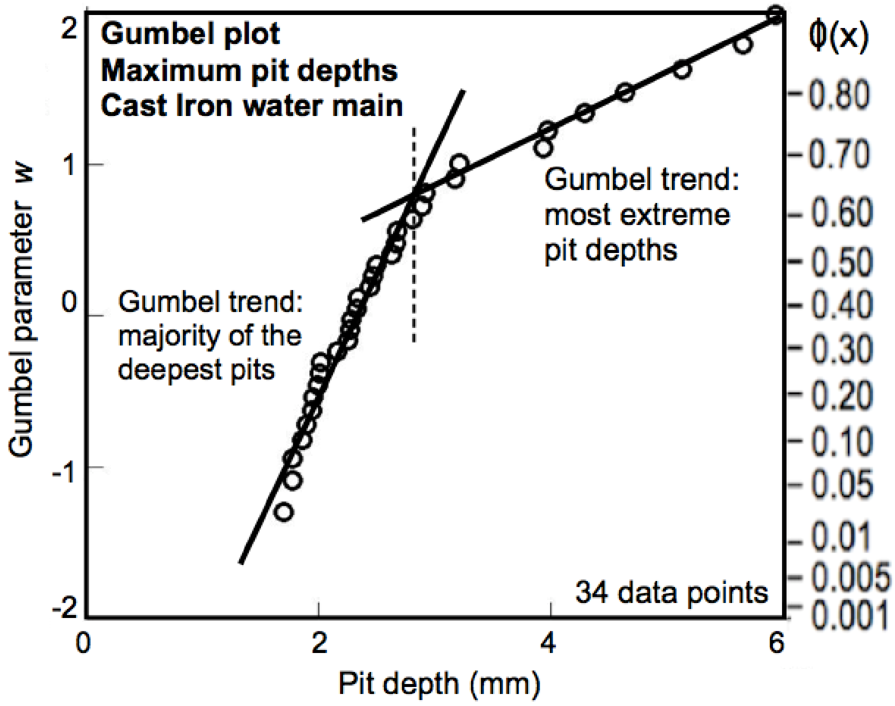

Figure 3. Gumbel probability plot for pit depths on a section of cast-iron pipe after 80 years of exposure, showing that the data overall are not representable by a single linear trend. The trend for the deeper pits is closely linear and can be interpreted as Gumbel distributed.

4. Discussion

The cases shown in Figures 1–3 are examples of the trending of the maximum pit-depth data showing that the most extreme pit depths tend to follow a trend that is not consistent with the rest of the data. However, they are not 'arch-typical', and there are many sets of pit-depth data for other pipes that do not show exactly the same patterns as in Figures 1–3. Many data sets show non-linear, discontinuous trends, but they often show less obvious departures from the main trend compared with those shown in Figures 1–3. A number of examples are available [25]. The reason for this variability in trending, including those in Figures 1–3, has to do with the differences in environmental conditions between the pipes, or with changes in the mechanistic behavior of pitting with exposure period, or both. The classic example of the influence of mechanistic behavior on Gumbel trending is that of wind speeds from windstorms versus wind speeds from thunderstorms, first described, in extreme value terms, by Gomes and Vickery [26]. They identified that records of maximum windspeeds should be separated from those of thunderstorm events and that these two cohorts have different trends on a Gumbel plot. Thus, for indiscriminate recording, in a given record period, the proportion of the record that includes thunderstorm events will determine whether there is a discernible difference in extreme value trending. It is likely that a parallel scenario will hold for maximum pit depths, but, to ascertain this, some remarks need to be made about the mechanisms involved in the development of maximum pit depth and also about the environmental conditions.

The conventional view of the development of the depth of pits is one of continual development with increased exposure conditions (i.e., period of exposure). This is likely the case for shorter exposures (days or weeks) and is convenient for theory development. A monotonic development of pit depth with time has the superficial support of plots of pit depth vs. time obtained from longer-term field tests, up to 16 years in marine conditions [27] and for 12 or more years in various soils [28]. However, the data on which such plots are based can best be described as 'scant'—insufficient to discern subtle changes in behavior. Changes in pit-depth development should be expected, based on the theoretical observations that the potential to drive pit deepening runs out as the pit becomes deeper [29,30]. When this is coupled with a more detailed analysis, the conclusion is that when the maximum pit depth is reached, sideways pit expansion is possible [31]. This opens the possibility for the development of plateaus from amalgamated pits, with new pitting occurring on the plateaus, leaving a step-wise incrementation of pit-depth development, consistent with observations for steels exposed for extended periods [32]. Not all pit development will be at the same rate for various reasons, but mostly because pitting is initiated at inclusions and imperfections in the steel (or cast iron), with various electrochemical potential implications. Overall pit-depth development will be dominated by the extreme-depth pits (Figure 4). It also may be held responsible for the variability in what is normally considered to be 'uniform' or 'general' corrosion. Provided the steel is reasonably uniform and isotropic, the pit-depth increments can be expected to be similar, resulting essentially and primarily from the differences in electrochemical potential [33].

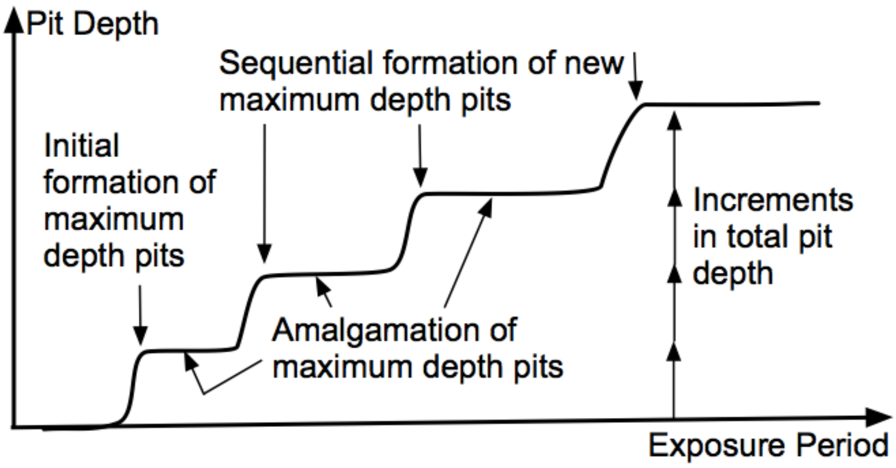

Figure 4. Schematic representation of the deepest observable pit depths and the increments that occur in that depth with an increased exposure period, showing also the periods during which the amalgamation of pits occurs and that these periods increase in duration in time as corrosion develops under an increased build-up of rusts.

Environmental factors may also have an influence on the trends of the Gumbel plots. For the external corrosion of cast-iron pipes in soils (Figure 3), differences between compaction of soil around the pipe have been identified as a significant factor in the earlier corrosion and pitting of the external surface of the pipe, with, in some cases, very deep pit depths when local compaction was poor [24]. For the internal corrosion of water-injection pipelines (Figure 1), the analogous scenario is the deposition of debris (rusts and sands) within the pipeline, a matter that depends much on the effectiveness and maintenance of the upstream filtration system (private correspondence). Evidence from actual operations, which is not available in the open literature, shows that the debris collected downstream can vary considerably between pipelines.

For production pipelines (Figure 2), the material entering the pipeline with the crude oil and the water and sand content is likely to be much more variable than it is for water-injection pipelines, as can be seen from the typical compositions of crude-oil streams [34]. Again, together with the effect of periods of no or low flow with debris deposition within the pipelines and the resulting under-deposit corrosion, the variability in the crude oil stream's composition is likely to have an influence on the extreme pit depths.

At first sight, it is remarkable that the three quite distinct operational environments—water of some undefined quality, crude oil and water in soil—produce essentially similar topologies for the Gumbel plots for the values observed for the maxima in pit depth and that they do so for steels and for cast iron. The latter is perhaps least surprising since it has been known for many years [35] that metals with a very high proportion of Fe in their composition corrode in 'general' corrosion in a similar manner and at a similar rate, and it has been assumed that the same applies for the severity and the rate of pitting corrosion. The common feature for the three environments is the presence of water. As noted, crude oil has a sizeable proportion of water in its overall composition (i.e., the 'water-cut'), and it is this water that is crucial to the processes of corrosion and pitting. For example, the effect of chlorides, often blamed for severe corrosion, is largely transient since it has been shown [36–38] that they have little or no effect on corrosion in areas or zones shielded from water velocity, as will occur within pits after the deposition of rust products on the pipe walls. Again, short-term experimental observations showing accelerating corrosion under water-velocity conditions may be valid for short-term exposures but have little relevance to the long-term exposures relevant for infrastructure (unless the velocities are so high that rust deposition does not occur).

The extreme right-hand trends in Figures 1–3 can be used to estimate the relevant parameters for the Gumbel extreme value distribution, and this can be used, in principle, in Equation (4) to estimate the probability of pipe wall perforation. However, it is noted that the Gumbel parameter w is directly related to the probability of exceedance (i.e., $=1 - \phi(y)$), where ϕ is shown on the right axis in each of the Gumbel plots in Figures 1–3. This then allows a direct estimate to be made of the probability of a pit depth greater than the nominated value. In this case, with most of the uncertainty residing in the maximum depth of pitting, the application of Equation (4) is not needed.

Finally, the trends shown in Figures 1–3 all indicate that the probability of exceedance is considerably greater than using the Gumbel trend through the bulk of the data to estimate the extremes. To be clear, this has been recognized in some application areas, such as for the offshore oil and gas sector [20]. Evidently, in their pipeline asset management, they have used the classical, entirely empirical, notion of the 'domain of attraction' in extreme value theory, recognizing the potentially serious environmental and economic implications of under-estimating the probability of pipe-wall perforation, not only for production pipelines but also for natural-gas pipelines and for water-injection systems. The present exposition of the development of corrosion pitting can be considered to have provided theoretical justification.

5. Conclusions

Extreme pit-depth data for water-injection, oil production and water-supply pipelines show distinctly discontinuous but linear trends when plotted on a Gumbel plot as is consistent for maxima as extremes. This is despite pitting for the water injection and oil production occurring on the inside of steel pipes and that of water-supply mains occurring on the outside of the pipes in contact with soils and water in soils. In all cases, it is possible for the most extreme of the pit depths to follow a Gumbel trend much flatter, and therefore, with much greater variance, than the bulk of the maximum pit depth data. This implies longer right-hand 'tails' for the distribution of that part of the data and potentially greater probabilities of the pit depth exceeding a given pipe wall thickness. Evidently, understanding this phenomenon and being able to evaluate it from cohorts of extreme pit-depth measurements is crucial for asset management and for estimating asset sustainability.

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