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ADVANTICA TECHNOLOGY

R5093 *January 2002*

THE USE AND ABUSE OF DAMAGE AND FAILURE DATA FOR THE PURPOSE OF STRUCTURAL RELIABILITY AND RISK ASSESSMENTS OF ONSHORE PIPELINES

Confidential *Restricted to UKOPA Fault Data Base Group & Advantica*

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Executive Summary

Pipeline designers and operators generally acknowledge that complex combinations of failure mitigating measures are needed to ensure safe operation of onshore high-pressure pipelines. Such measures include appropriate choice of wall thickness, material grade, burial depth, hydrostatic test pressure, weld type and coating type. Additionally, a number of in-service activities including in-line inspection, Close Interval Surveys (CIS), Direct Current Voltage Gradient (DCVG) measurements and Pearson Surveys are undertaken to ensure that deterioration of the pipeline is mitigated.

In the UK recommended values of parameters associated with many of the above activities are given in the design code IGE/TD/1 [1] and adherence to these recommendations has resulted in approximately 0.5 million kilometre years of operation of high pressure transmission pipeline without any loss of life due to pipeline failure. It is thus considered that the recommendations given in IGE/TD/1 are generally conservative.

However, the actual levels of conservatism (i.e. by how much can the limiting values of any individual parameter, or combinations of parameters, be relaxed before an unacceptable safety record would result) are generally unknown. It is also generally unknown which parameters provide the most effective mitigation in given situations. Such knowledge would be of significant value to pipeline operators and designers since it could potentially allow significant savings in costs. Areas of particular interest might be reducing wall thickness, pressure uprating and pipeline life extension.

In non-safety critical industries, such as manufacturing, information on system reliability can be obtained empirically by recording measured changes in failure rates/frequencies due to changes in various system operating parameters. Large databases can be constructed from which parameters such as mean time between failures (MTBF) can be obtained. Subsequently, techniques such as reliability centred maintenance (RCM) are used to determine the most cost effective operating scenarios.

However, the above approach cannot be applied to the pipeline industry since failure rates are necessarily required to be so low that it would be impossible to construct a statistically significant database of failure incidents. In these situations it is more appropriate to refer to the probability of failure (Pf) rather than failure frequency. It thus follows that pipeline reliability (1-Pf) can only be determined by gathering additional information from alternative sources to failure records. An approach that is well suited for this purpose is structural reliability analysis (SRA).

SRA combines theoretical and empirical structural mechanics with uncertainty analysis of structural parameters in order to determine failure probabilities. The essence of the approach is to use parameters for which statistically significant numbers of measured values are often available (e.g. wall thickness and yield strength) in predictive models (limit state functions) in order to predict the uncertainty in parameters for which statistically significant databases are unavailable (e.g. leak & rupture incidents).

An essential requirement of the SRA approach is the availability of limit state functions associated with the failure modes that could credibly affect given pipelines. Such failure modes would often include those associated with external impact, internal/external corrosion and fatigue. Various limit state functions associated with each of these failure modes are available and they generally comprise parameters that can be categorised as geometrical, material, load or defects/damage. The variability in geometrical and material parameters can be obtained from mill certificates or, in the absence of these, inferred generically. The loadings are usually available from operating records. However, the parameters that usually have the most effect on the probability of failure are the defect parameters. This is because the limit state functions are often most sensitive to these parameters and they are also subject to greater uncertainty than the others. It thus follows that a database describing the uncertainty in defects/damage is an important requirement for the effective use of SRA.

The purpose of this report is to illustrate the benefits of using SRA for predicting failure probabilities using the recently constructed United Kingdom Onshore Pipeline Operations Association (UKOPA) fault database and, of equal importance, to highlight the dangers of using sparse records of failures for the purpose of predicting future failure probabilities.

The use of SRA for the purpose of quantifying the contributions of individual mitigating measures to reliability, and hence for identifying the most cost effective measures, is illustrated based on a consideration of the effect of wall thickness.

Conclusions

1 The SRA approach has highlighted the crude nature of determining the failure probability from the use of leak data. For high pressure pipelines, leak data is so sparse that meaningful failure frequencies can only be derived for broad categories of pipelines parameters.

2 For circumstances where leak data are sparse, SRA enables the failure probability to be calculated for any combination of pipeline parameters. This shows a clear need for predictive methods to determine failure probability.

3 SRA has been used to determine the failure probability of onshore pipelines due to external interference and corrosion. The SRA approach has demonstrated that pipeline wall thickness has a strong influence on failure probability.

4 The importance of having a predictive tool for determining failure probabilities in situations were failures are infrequent has been highlighted and the relevance of the approach to land-use-planning issues has been discussed.

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1 INTRODUCTION

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The use of SRA for the purpose of quantifying the contributions of individual mitigating measures to reliability, and hence for identifying the most cost effective measures, is illustrated based on a consideration of the effect of wall thickness.

2 ROLE OF THE UKOPA DATABASE

A primary objective of collecting any historical data is to learn about the past in order to make forecasts about the future.

However, the data to be collected and the procedures for analysing these data in order to make forecasts are very dependent on the nature of data and the implication of the predictions. In order to understand the importance of the contribution that the UKOPA database makes towards the UK and other pipeline industries it is worth briefly considering data and data analysis issues faced by other industries.

2.1 Process Industries

In the process industries 'mean time between failures' (e.g. plant component failures) are often recorded in terms of 100hrs of operation and large databases are readily constructed. Over the years failures have occurred by the tens and hundreds of thousands and even millions. These failures usually have no safety implications and techniques such as reliability centred maintenance are employed to interpret the data and to establish strategies for minimising cost. In doing so a number of failures are accepted as part of the business strategy and any cost involved in trying to further reduce the failures would not make business sense. In this case there is no requirement for predictive modelling of the failure mechanism since there is an abundance of data for the purpose of predicting failure rates.

2.2 Nuclear Industry

In the nuclear industry catastrophic failures of reactor pressure vessels have immense safety implications and are therefore to be avoided at any cost. Central to most safety cases for nuclear reactor pressure vessels in the UK is the incredibility of failure argument which requires that sufficient mitigation is in place to ensure that probability of failure is less than 10^{-7} per reactor year.

However, a simple analysis of historical failures that have occurred worldwide suggests that current failure rates are much higher than this. Simply dividing the number of known serious incidents (perhaps 5) by the total number of operating years (500 reactors operating for 30 years = 15,000 reactor years) results in a failure frequency of $3x10^{-4}$ per reactor year. This figure is, of course, not a true indication of the general failure probabilities of nuclear reactor pressure vessels but rather serves to illustrate the fundamental error of applying the ‘frequentist’ approach to situations for which statistically significant data can never be made available. In these situations historical failure data cannot be used to make future predictions and a clear understanding of all potential failure modes and the measures required to mitigate them is required. Predictive modelling, conservatively taking account of all uncertainties, is the only viable approach in these situations.

2.3 The Onshore Pipeline Industry

The onshore pipeline industry clearly lies between the above two extremes but is most certainly far closer to the nuclear industry than the process industry. This is indeed borne out by the number of incidents involving release of product recorded in the UKOPA database There have been about 150 such releases during 500,000kmyr of operation giving a release frequency of $3x10^{-4}$ releases / kmyr. Taking the number of incidents (nine) that have occurred in the last five years (corresponding to about 100,000kmyr of operation) results in a frequency of $9x10^{-5}$ releases per km yr, which possibly reflects improvements in terms of operational reliability, i.e. a reduction by a factor of 3.

It should be noted that none of the 150 releases cited above resulted in a loss of life. This is because the majority of the releases were from very small holes. It thus follows that the above frequency is not representative of cases involving safety implications. These situations may often demand much lower probabilities in order to achieve an acceptable level of risk and therefore predictive modelling still remains the only sensible option.

Also if one wishes to determine the appropriate frequency associated with a given combination of parameters or indeed associated with one individual parameter (e.g. wall thickness) the available data become few. Claiming a failure frequency based on 2 failures associated with a given wall thickness divided by the exposure time of all pipelines in that category is not very meaningful. Recourse to predictive modelling is thus essential.

Moreover, there has only been one ‘full bore’ release in the last five years.

It thus follows that predictive modelling that derives failure probabilities from damage data is an essential requirement in order to understand the reliability of high-pressure pipelines and in particular to understand how this quantity depends on pipeline parameter combinations.

This report gives a brief description of the predictive modelling techniques developed by Advantica Technologies and provides a number of example case studies in which the UKOPA database is used in conjunction with these models to derive failure probabilities.

Failures due to the occurrence of both external interference and external corrosion are addressed and the variability of the probability of failure due to varying parameters such as nominal wall thickness is illustrated.

3 STRUCTURAL RELIABILITY ANALYSIS

The modelling technique developed by Advantica involve a combination of structural mechanics and probability theory and is known as structural reliability analysis (SRA). SRA is based on combining theoretical and empirical structural mechanics with uncertainty analysis, and is briefly described below. Recent applications of SRA to onshore pipelines are given in [1]-[6].

The method comprises six elements. These are

- Establishment of Limit States
- Identification of Failure Modes
- Formulation of Limit State Functions
- Uncertainty Analysis
- Evaluation of Failure Probability
- Assessment of Results

The relationship between these items is shown schematically in Figure 1 and a brief description of each of them and the role they play in the overall analysis is given below.

A detailed description of the overall methodology is given in [4].

The primary focus of the present study is on the application of the methodology to the limit states leak and rupture caused by failure modes associated with external interference and external corrosion damage.

3.1 Limit State Functions

3.1.1 External Interference

In the most general situation external interference leads to a dent containing a gouge in the pipeline wall. Gouges situated in dents are assessed using a fracture mechanics approach assuming that the gouge behaves as a crack. The limit state function is given by

$$K_r = S_r \left[\frac{8}{\pi^2} \ln \sec\left(\frac{\pi}{2} S_r \right) \right]^{-\frac{1}{2}} \quad \textbf{(1)}$$

where the dimensionless parameters K_r and S_r are given by

$$K_r = \frac{\left[\sigma_m Y_m(a,w) + \sigma_b Y_b(a,w) \right] \sqrt{\pi a}}{K_{IC}} \quad \textbf{(2)}$$

and

$$S_r = \frac{\sigma_m\left(1-\dfrac{a}{M\,w}\right)}{\sigma_f\left(1-\dfrac{a}{w}\right)} \quad \textbf{(3)}$$

In the above equations σ_m is a membrane stress given by

$$\sigma_m = \sigma_h\left(1-1.8\frac{D}{2R}\right) \quad \textbf{(4)}$$

and σ_b is a bending stress due to the presence of a dent of depth D, given by

$$\sigma_b = 10.2\,\sigma_h \frac{R}{w}\frac{D}{2R} \quad \textbf{(5)}$$

where σ_h is the hoop stress given by

$$\sigma_h = \frac{P\,R}{w} \quad \textbf{(6)}$$

and R and w denote the pipeline radius and wall thickness respectively.

The quantities Y_m and Y_b are functions of gouge depth, a, and represent normalised stress intensity factors for an edge cracked strip in tension and bending respectively. The Folias factor, M, is given by

$$M = \left[1+0.26\left(\frac{L}{\sqrt{Rw}}\right)^2\right]^{\frac{1}{2}} \quad \textbf{(7)}$$

where L is the gouge length. The material flow stress is denoted by σ_f and the material fracture toughness, K_{IC}, is found from the Charpy energy using the following correlation

$$K_{IC} = \left(\frac{E\,C_{v0}}{A}\right)^{\frac{1}{2}}\left(\frac{C_v}{C_{v0}}\right)^{\frac{1}{2b}}, \quad \textbf{(8)}$$

where E is the Young's modulus of the material, A is the area of the Charpy test specimen, b is a dimensionless parameter and C_{v0} is a reference Charpy energy.

The length of a gouge determines whether failure of the dent/gouge defect will result in a rupture or a leak. The failure of a defect leads to the creation of a through wall defect. If the length of the resulting through wall defect is greater than a critical length L_c given by

$$L_c = \sqrt{\left[\left(\frac{\sigma_h}{1.15\sigma_y}\right)^{-2} - 1\right]\left(\frac{Rw}{0.4}\right)}, \qquad \textbf{(9)}$$

where σ_y is the yield strength of the material, then a rupture will occur. Conversely, if the length is less than the critical length then the through wall defect will be stable and the failure will lead to a leak.

3.1.1.1 Incident Rate

The incident rate for external interference, i.e. the rate at which new gouges occur on the pipeline system, depends on the area classification (Rural or Suburban). The incident rate is found by dividing the number of gouges in each area class by the exposure in that area class. This information is found in the UKOPA Fault Database and the following results are obtained,

Rural area incident rate = 665 / 443447 = 1.50 x10^{-3} / kmyr

Suburban area incident rate = 341 / 46578 = 7.32 x10^{-3} / kmyr

The data show that the suburban area incident rate is approximately 5 times greater than the rural area rate.

3.1.2 External Corrosion

The limit state function for corrosion defects relates the defect depth at failure to the defect length and hoop stress and is given by

$$a(t) = a_c \qquad \textbf{(10)}$$

where a is the actual depth of the defect which depends on time, t, and a_c is the depth at failure which is related to the wall thickness, *w*, hoop stress, σ_h, and ultimate tensile strength, σ_u, through the expression

$$a_c = w\left[\frac{1 - \dfrac{\sigma_h}{\sigma_u}}{1 - \dfrac{\sigma_h}{\sigma_u}Q^{-1}}\right] \qquad \textbf{(11)}$$

where Q is a length correction factor given by the expression

$$Q = \left[1 + 0.31\left(\frac{l}{\sqrt{2Rw}}\right)^2\right]^{\frac{1}{2}} \qquad \textbf{(12)}$$

in which l is the axial length of the corrosion defect and R is the mean diameter of the pipeline, [7]. The length of a corrosion defect determines whether failure will result in a rupture or a leak. The failure of a corrosion defect leads to the creation of a through wall defect. If the length of the resulting through wall defect is greater than a critical length, L_c, given by

$$L_c = \sqrt{\left[\left(\frac{\sigma_h}{1.15\sigma_y}\right)^{-2} - 1\right]\left(\frac{Rw}{0.4}\right)} \quad \textbf{(13)}$$

where σ_y is the yield strength of the material, then a rupture will occur. Conversely, if the length is less than the critical length then the through wall defect will be stable and the failure will lead to a leak.

3.1.2.1 Corrosion Incident Rate

The incident rate for external corrosion, i.e. the rate at which corrosion defects occur on the pipeline system, depends on the type of coating. The incident rate is found by dividing the number of corrosion defects for each type of coating by the exposure in that area class. This information has been taken from the UKOPA Fault Database, with the results given in Table 1.

Coating Type	No. Defects / Exposure	Incident Rate (/kmyr)
Bitumen	261 / 20063	1.30 x10^{-2}
Coal Tar	752 / 417077	1.8 x10^{-3}
Polyethylene	14 / 31302	4.47 x10^{-4}
FBE	13 / 27525	4.72 x10^{-4}
Other/Unknown	77 / 22681	3.39 x10^{-3}
Total	1117 / 518828	2.15 x10^{-3}

Table 1: External Corrosion Incident Rates for Different Coatings.

3.2 Uncertainty Analysis

The above limit functions comprise a number of parameters. In practice all of these parameters are subject to uncertainty. However, the magnitude of this uncertainty is greater for some parameters than others. Furthermore some parameters have a more significant effect on the probability of failure than others. Based on experience, the parameters that have been found to have the most marked effect on failure probability are:

- Yield strength, σ_y
- Wall thickness, w
- Charpy Energy, C_v

- Dent depth, D
- Gouge depth, L
- Gouge length, a
- Corrosion defect depth, $a(t)$
- Corrosion defect length, l

and the uncertainty in these parameters is addressed in this study. All other parameters are assigned appropriate deterministic values.

3.2.1 Yield strength, ultimate tensile strength and wall thickness

The uncertainty in σ_y, σ_u and w is usually represented by Normal or Log-Normal distributions and the characteristic fit parameters are obtained from simple statistical analyses of data given on mill certificates. In situations were no or few certificates are readily available, reasonable estimates of uncertainty can be obtained based on the assumption that the mean value is 10% higher than specified minimum values.

3.2.2 Gouge Length & Depth

The uncertainty in D, L and a are obtained from the information recorded in the UKOPA Fault Database.

The pipeline exposure (operational history in kilometre years) recorded in the database totals 443447 km years for Rural area pipelines and 46578 km years for Suburban pipelines.

The UKOPA Fault Database contains 1006 records of gouge length and gouge depth for 1006 gouges caused by external interference,185 of which are associated with a dent. Of the 1006 gouges, 665 occurred on pipelines operating in rural areas and 341 occurred on pipelines operating in suburban, semi-rural or urban areas (referred to collectively as suburban areas for brevity).

For each record, nominal values of the wall thickness, material grade, operating pressure, diameter and other data pertaining to the pipe section containing the gouge are recorded. Statistical examinations of these data have revealed that there is no correlation between gouge depth, gouge length and any of the other parameters. Also the gouge dimensions in rural areas are not noticeably different than those on the gouges found in suburban areas. Hence, it was deduced that the uncertainties in both gouge length and gouge depth can be described by unique (independent of other pipeline properties and location) probability density functions.

Consequently, separate Weibull distributions given by

$$P(x) = 1 - \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \qquad \textbf{(14)}$$

where $P(x)$ is the cumulative distribution function, were fitted to the gouge depth and gouge length records. The resulting fits (red) to the data (blue) are shown in Figures 2 and 3 respectively and the respective fit parameters, α and β are shown in Table 2.

Parameter	Units	α	β
Gouge Depth (a)	mm	0.63	0.73
Gouge Length (L)	mm	0.84	183.6

Table 2: Weibull fit parameters for gouge depth and gouge length pdfs

3.2.3 Dent Depth

Experimental tests have confirmed a relationship between denting force and dent depth that is dependent on pressure, yield strength, wall thickness and diameter. It thus intuitively follows that; unlike for gouge depth and length, no unique pdf can be used to describe the uncertainty in dent depth. Contrarily, an individual pdf is required for each (p, σ_y, w, D) combination.

Due to the large number of possible combinations of (p, σ_y, w, D) no statistically significant data exist from which to construct a pdf for dent depth relevant to a particular combination. It has thus been necessary to make recourse to modelling based on structural mechanics.

Previous experimental testing had allowed a relationship between dent force and dent depth to be constructed and the functional form of this relationship is

$$D = \left[\frac{F}{0.49\sqrt{\left(w + \frac{1.4pR}{1.15\sigma_y}\right)}(80w\sigma_y)^{\frac{1}{4}}} \right]^{2.38} \quad \textbf{(15)}$$

The implication of this relationship is that the uncertainty in dent depth can be inferred for a particular combination of (p, σ_y, w, D) provided that the uncertainty in dent force is known. Unfortunately, no data describing the uncertainty in denting force are readily available.

The approach adopted by Advantica was thus to construct a distribution of forces from the recorded dent depths given in the UKOPA database. The essence of this approach was to convert each recorded dent depth into a probable dent force using the empirical relationship given in (15), taking account of the uncertainties in p, σ_y, w and D. The blue data points in Figure 4 illustrate the probable dent force values and a Weibull fit to these data $(\alpha = 2.12, \beta = 110.2)$ is shown by the red curve.

The dent force pdf can be used in conjunction with the relationship between dent force and dent depth given above to determine the dent depth pdf for any combination of (p, σ_y, w, D).

3.2.4 Corrosion defect depth

Corrosion is a time dependent process involving the growth of defects. Thus the distribution of defect depth will change with time during the life of a pipeline. It is therefore necessary to describe the probability density function of a defect with depth a as a time dependent quantity.

Data for corrosion defect depth have been taken from the UKOPA Fault Database.

The Weibull probability density function has been found to give the best fit to the data, with parameters

$$\alpha = 2.3328$$
$$\beta(t) = 0.8316 \ln(t) + 0.9513 \qquad \textbf{(16)}$$

where t represents the time in years since commissioning.

3.2.5 Corrosion defect length

In order to construct a defect length distribution it was assumed that the length of the corrosion was equal to the length of the defect in the coating, whereas in reality the length of the corrosion defect may extend slightly beyond that. Provided that there is no further loss of coating around the perimeter of the defect it can be further assumed that the length of the defect remains constant with time. The length of a corrosion defect will actually increase with time beyond the boundaries of the coating defect until the products released by corrosion protect it, but it has been implicitly assumed that this increase in length is negligible.

The distribution found to give the best fit to the data given in the UKOPA database for corrosion defect length is a Weibull probability density function with $\alpha = 0.88$ and $\beta = 129.93$.

3.3 Evaluation of the Probability of Failure

A failure in any structure will occur if the resistance to failure, R, is lower than the load causing the failure, S; and give the failure criterion as

$$R < S, \qquad \textbf{(17)}$$

where R is derived from material and geometric properties, and S is derived from operational loads, fault loads, damage and deterioration. The determination of R and S can be a very complex process depending on the failure mode under consideration since R and S may be inter-dependent on a number of other parameters. The generalised forms of the probability of failure are given below when independent of time and when time-dependent.

The probability of failure for when the failure mode is independent of time (e.g. instantaneous event such as failure of a dent/gouge defect) is given by

$$p_f = p_{inc} \int_0^{\infty} \int_R^{\infty} p(R,S)\,dS\,dR \qquad \textbf{(18)}$$

where $p(R, S)$ is the joint probability density function of R and S and p_{inc} is the incident rate. The probability given by the above expression is the probability of failure given that an instantaneous event has occurred.

When the failure mode is dependent on time (e.g. degradation process such as corrosion) there will be a gradual migration of (R, S) points from locations below the line $R = S$ to locations above the line $R = S$. The probability of failure within the time interval $(0, t)$ is given by

$$p_f(t) = p_{inc} \int_0^{\infty} \int_R^{\infty} p(R,S,t)\,dS\,dR \qquad \textbf{(19)}$$

where $p(R, S, t)$ denotes the joint pdf of R and S at time t. The expression denotes the probability of failure within the time interval $(0, t)$ because failure can take place at any time during the migration of the points across the line $R = S$.

As discussed above R and S are often dependent on a number of other variables that characterise a particular failure mode. A more precise expression for $p_f(t)$ is thus

$$p_f(t) = p_{inc} \iint_{G(x) \le 0} p(x_1, x_2, \ldots x_n, t)\,dx_1 dx_2 \ldots dx_n \qquad \textbf{(20)}$$

where $x_1, x_2, \ldots x_n$ denote the variables which characterise a particular failure mode and the function G is the limit state function. The joint pdf $p(x_1, x_2, \ldots x_n, t)$ depends on the joint pdf at time 0, $p(x_1, x_2, \ldots x_n, 0)$ and the time dependent degradation process involved. The relationship between these quantities is addressed in more detail in [2], for example.

Some of the above variables in (20) may be replaced by single values that result in the remaining variables being independent and the joint probability density function is replaced by the product of the individual probability density functions, [8]. However, regardless of the simplifications, the integration in (20) can rarely be undertaken in closed form and recourse is usually made to numerical integration, approximation techniques, or numerical simulation.

4 PIPELINE CASE STUDIES

4.1 Probability of Failure Due To External Interference

In this section the relation between the probability of failure due to external interference and wall thickness is investigated using the techniques described above.

Three notional pipelines have been analysed:

- 914 mm diameter, 75 bar & design factor (df) = 0.7
- 273 mm diameter, 98 bar & deign factor (df) = 0.7
- 218 mm diameter, 49 bar & design factor (df) = 0.25

The probability of failure of each of the pipelines due to external interference has been calculated for a range of combinations of wall thickness and grade chosen to maintain a design factor (df) of about 0.7 for the first two pipes and a design factor of about 0.25 for the third pipe.

The results of this analysis are shown by the blue curves in Figures 5-7 for the 914mm, 273mm and 218mm pipelines respectively.

It is seen from the three figures that the probability of failure decreases along a smooth curve as the wall thickness increases. The results thus illustrate that wall thickness plays a dominant role in mitigating failures due to external interference.

Also shown in Figures 5-7 by the red lines are the probabilities of failures that have been determined by the 'frequentist' approach; i.e. by dividing the number of leaks by exposure time. These data are also given in Table 3. The crudeness and inadequacies of the frequentist approach are illustrated by the comparison with the predictive approach.

Wall Thickness (mm)	Failure Frequency per km year
< 5	2.37×10^{-4}
5-10	6.80×10^{-5}
10-15	2.08×10^{-5}
> 15	0.0

Table 3: Failure Frequencies from Leak Database

4.2 Probability of Failure Due To External Corrosion

In this section the relation between the probability of failure due to external corrosion and wall thickness is investigated using the same pipeline dimensions and pressures as in Section 4.1, namely:

- 914 mm diameter, 75 bar & df = 0.7
- 273 mm diameter, 98 bar & df = 0.7
- 218 mm diameter, 49 bar & df = 0.25

The probability of failure of each of these pipelines due to external corrosion has been calculated for a range of combinations of wall thickness and grade chosen to maintain a design factor of about 0.7 for the first two pipes and a design factor of 0.25 for the third pipe.

The results of this analysis are shown by the blue curves in Figures 8-10 for the 914mm, 273mm and 218mm pipelines respectively.

It is seen from the three figures that the probability of failure decreases along a smooth curve as the wall thickness increases. The results thus illustrate that wall thickness plays a dominant role in mitigating failures due to external corrosion, but not as great as the failures due to the external interference.

The red lines in Figures 8-10 show the probabilities of failures that have been determined by the 'frequentist' approach; i.e. by dividing the number of leaks by exposure time. These data are also given in Table 4. The crudeness and inadequacies of the frequentist approach are illustrated by the comparison with the predictive approach.

Wall Thickness (mm)	Failure Frequency per km year
< 5	3.55×10^{-4}
5-10	4.40×10^{-5}
10-15	0.0
> 15	0.0

Table 4: External Corrosion Failure

5 APPLICATION

In this report, the weaknesses of using the frequentist approach to the determination of failure probabilities in situations where failures are infrequent have been identified. The advantages of, and indeed the need for, a predictive approach have been explained and illustrated through a number of worked examples.

The requirement for such an approach is particularly relevant to issues such as land-use-planning which calls for 'consistent' decisions to made on the acceptability of populated developments in the vicinity of high-pressure pipelines.

Land-use-planning involves both a consideration of the likelihood of occurrence of a failure and the potential consequences of a failure on the surrounding populations. It is thus important to remove inconsistencies that might arise from the frequentist approach if inconsistencies in land-use-planning advice are to be avoided. A description of how predictive modelling is combined with consequences in order to give consistent land-use-planning advice, taking account of issues such as 'aversion' to more severe consequences is given in [9].

6 CONCLUSIONS

1 The SRA approach has highlighted the crude nature of determining the failure probability from the use of leak data. For high pressure pipelines, leak data is so sparse that meaningful failure frequencies can only be derived for broad categories of pipelines parameters.

2 For circumstances where leak data are sparse, SRA enables the failure probability to be calculated for any combination of pipeline parameters. This shows a clear need for predictive methods to determine failure probability.

3 SRA has been used to determine the failure probability of onshore pipelines due to external interference and corrosion. The SRA approach has demonstrated that pipeline wall thickness has a strong influence on failure probability.

4 The importance of having a predictive tool for determining failure probabilities in situations were failures are infrequent has been highlighted and the relevance of the approach to land-use-planning issues has been discussed.

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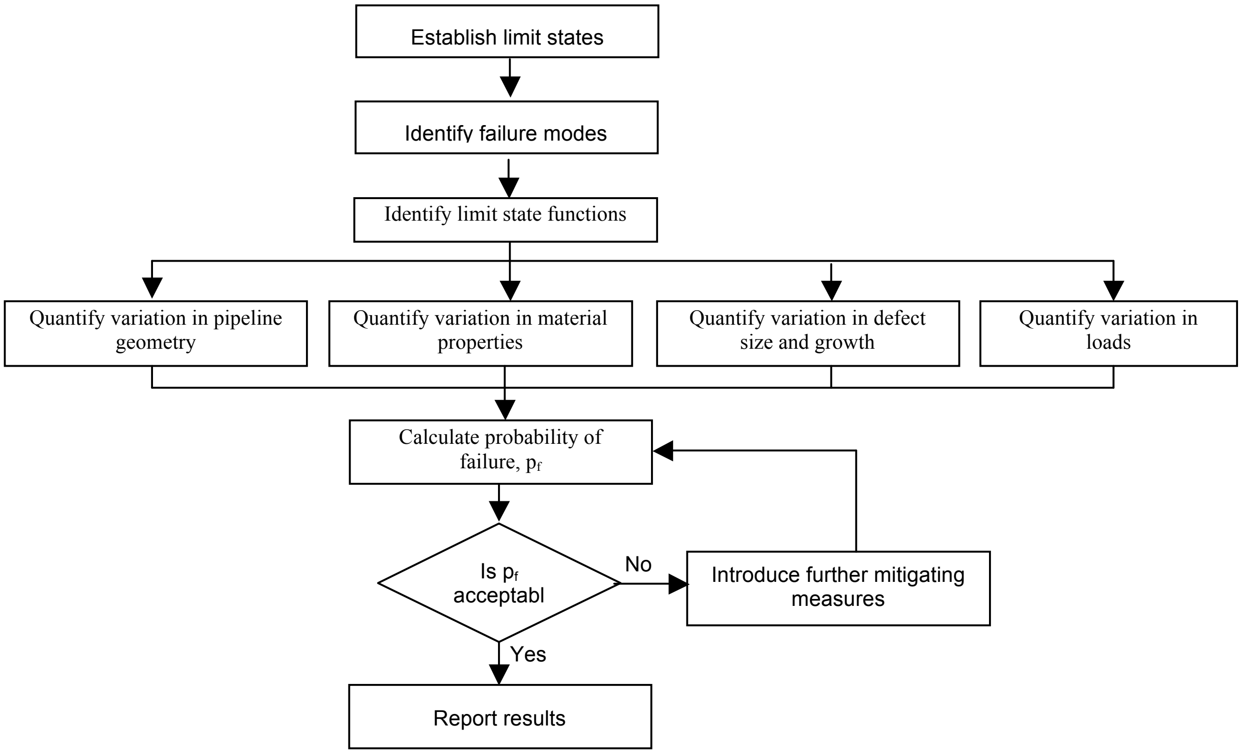

Figure 1: SRA Process

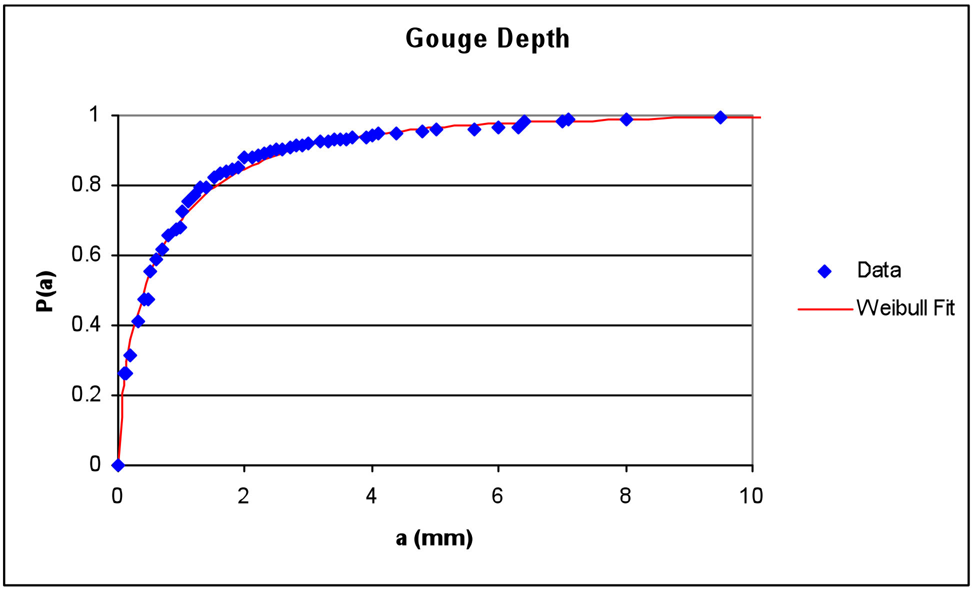

Figure 2: Distribution of Gouge Depth Data

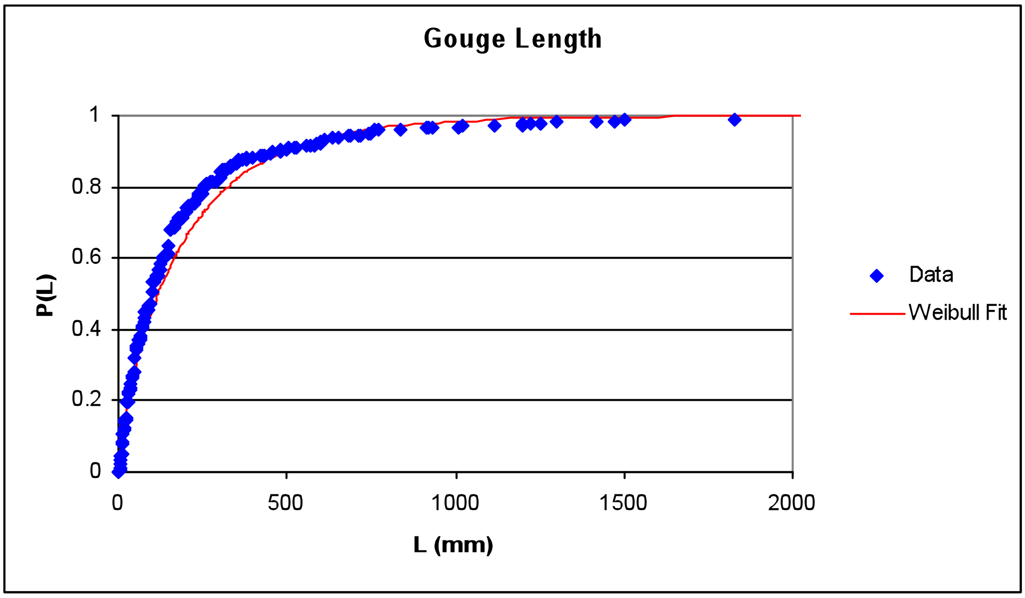

Figure 3: Distribution of Gouge Length Data

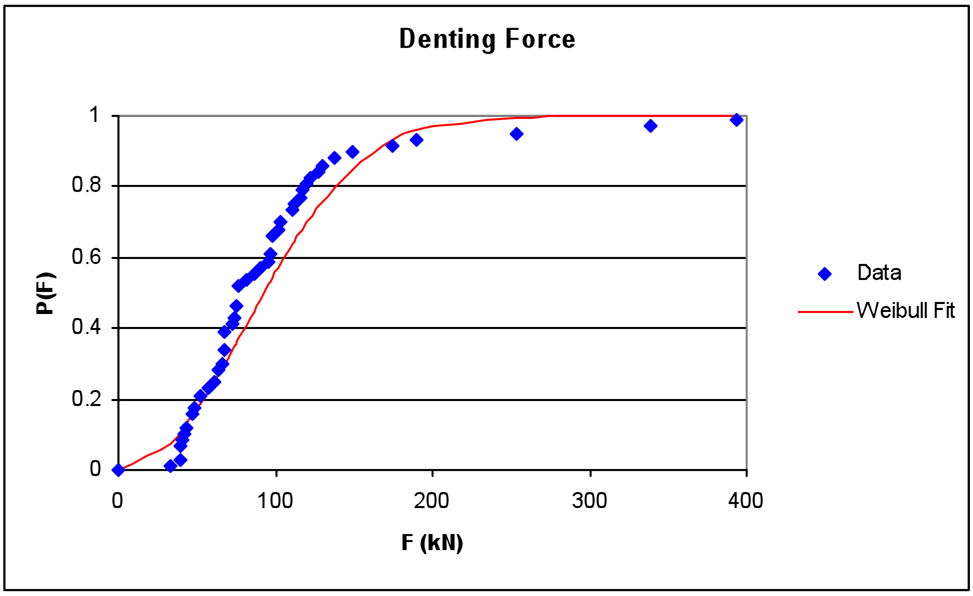

Figure 4: Distribution of Denting Force Data

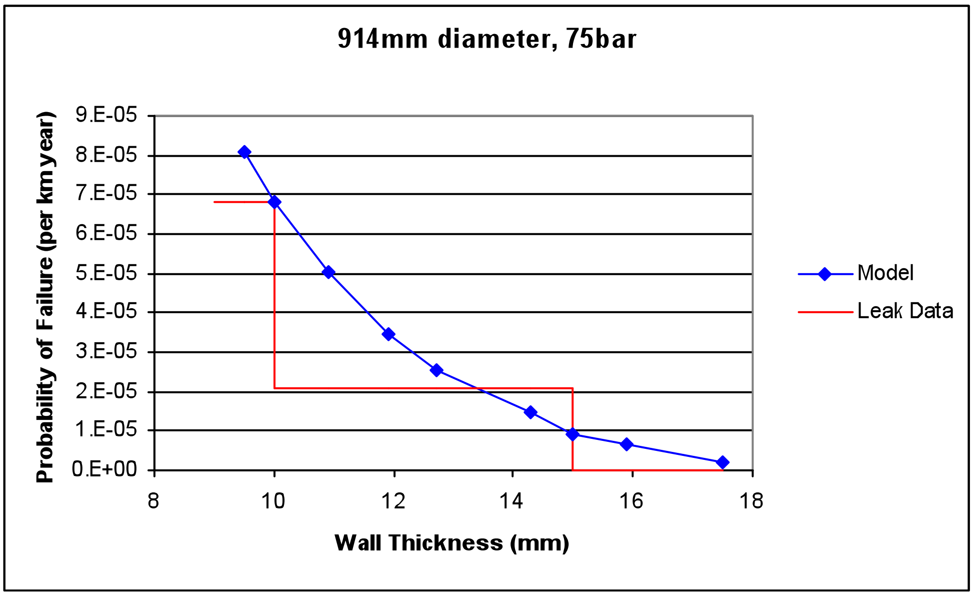

Figure 5: External Interference - Influence of Wall Thickness on Failure Probability

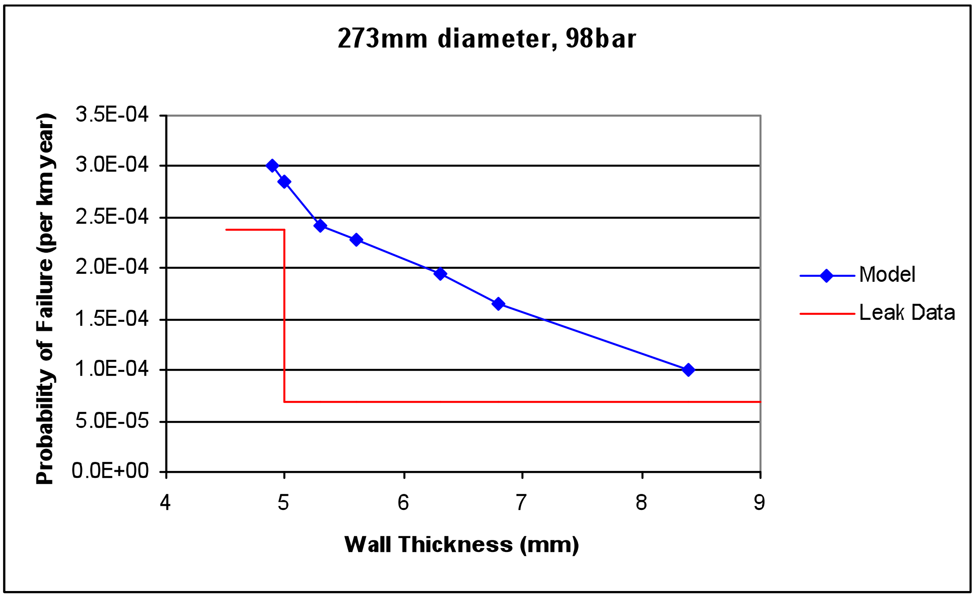

Figure 6: External Interference - Influence of Wall Thickness on Failure Probability

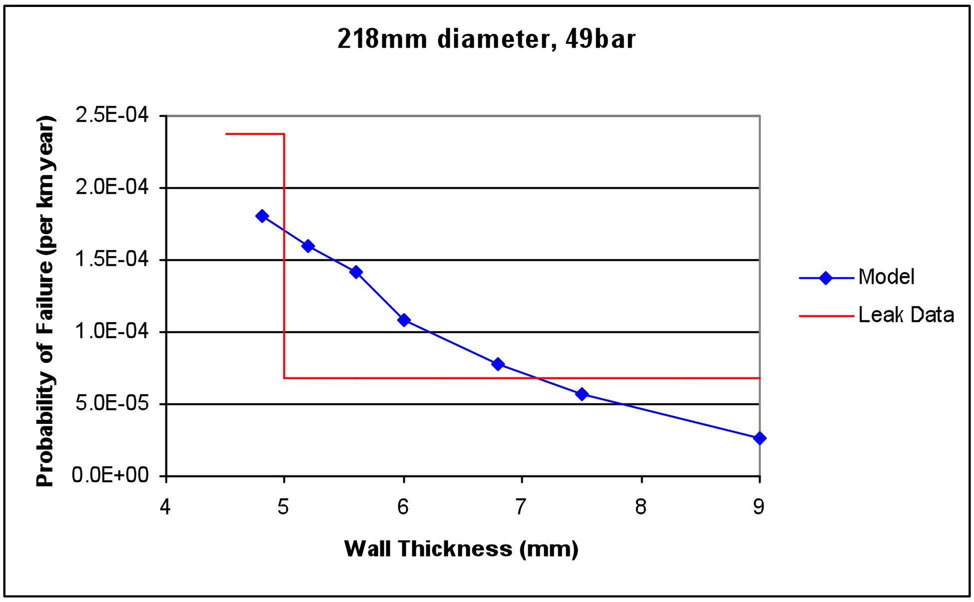

Figure 7: External Interference - Influence of Wall Thickness on Failure Probability

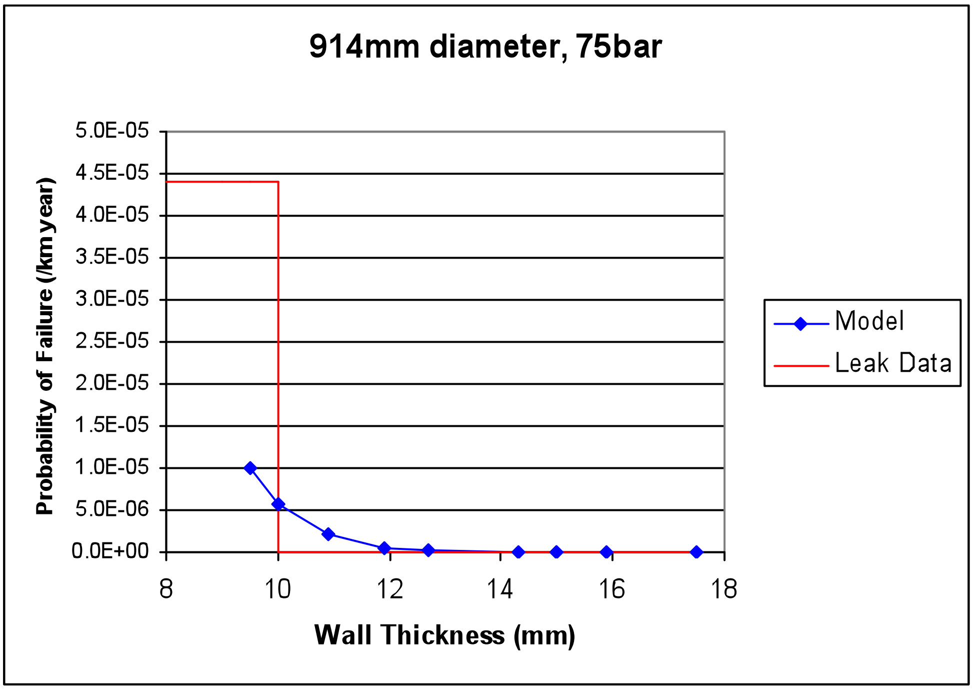

Figure 8: External Corrosion - Influence of Wall Thickness on Failure Probability

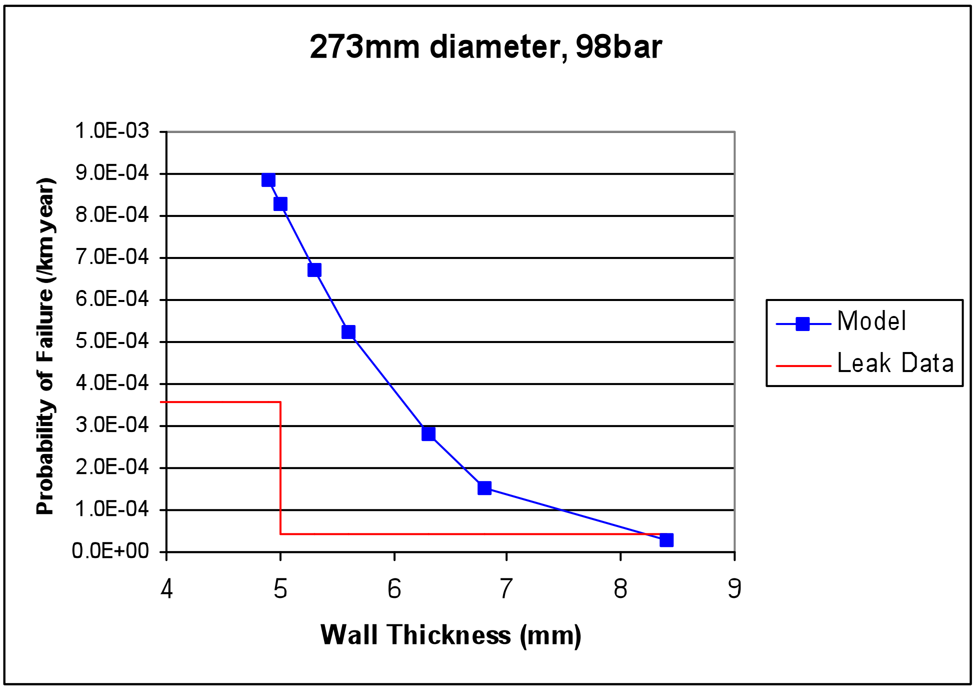

Figure 9: External Corrosion - Influence of Wall Thickness on Failure Probability

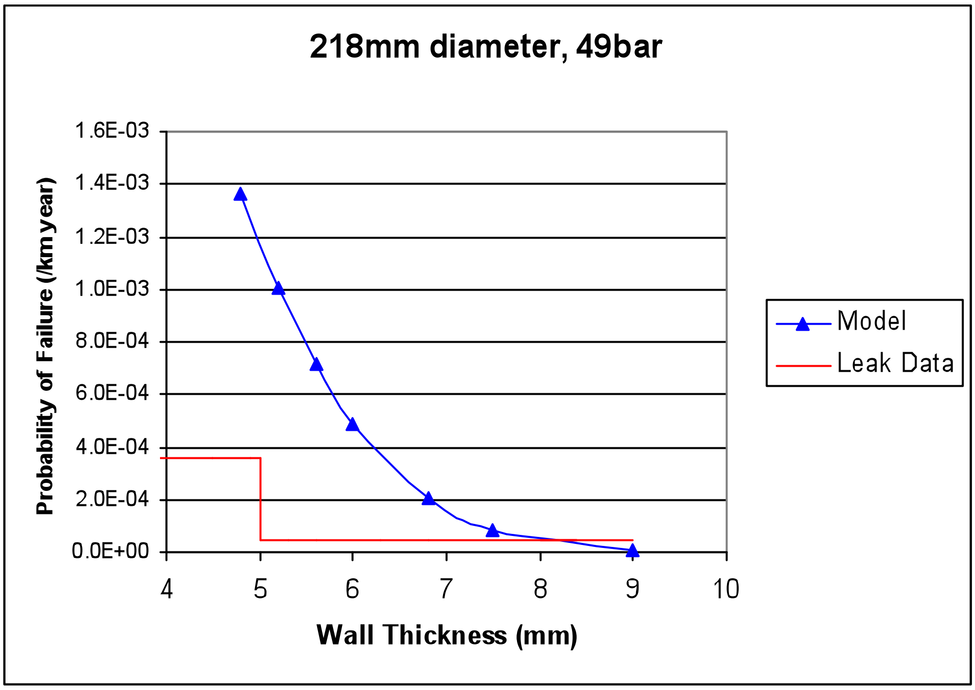

Figure 10: External Corrosion - Influence of Wall Thickness on Failure Probability