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ABSTRACT

The Health and Safety Executive (HSE) use the PIPINV3 (PIPeline INtegrity) model to predict failure frequencies for major accident hazard (MAH) pipelines. The failure frequencies generated by PIPINV3 are used as part of a pipeline risk assessment process to create land use planning (LUP) zones around the pipeline. HSE uses the LUP zones to provide guidance to local planning authorities in Great Britain on proposed developments near a pipeline, for when there are potential modifications to an existing pipeline, and for proposed new pipelines. PIPIN was first developed in the 1990s. It has been rewritten to: incorporate a Monte Carlo solution method; update the scientific basis of the model, and update the historical data used in the model. This paper details the science within PIPINV3 and also describes how predicted failures are apportioned amongst representative hole sizes used by HSE to model different severities of failure. Comparison tests with an earlier version of the model have been made using test data from 584 natural gas pipelines, a subset of pipelines from the UK natural gas network. The tests indicated that the use of PIPINV3 reduced predicted failure frequencies on average. This leads to either no change or a reduction in the size of the calculated LUP zones in most cases.

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KEYWORDS HSE; PIPIN; pipelines; failure frequencies; fracture mechanics; third party activity

Introduction

In quantitative risk assessment (QRA), failure rates are often based on historical data (Mannan, 2012), where the number of failure incidents is divided by the estimated number of relevant equipment years. For pipelines, a different approach has been developed that relies on fracture mechanics to

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determine a material's reaction to stresses that are imparted on it. This approach has been used by the regulators in the UK and the Netherlands (National Institute for Public Health and the Environment [RIVM], 2014), as well as some operators (Acton, Baldwin, & Dimitriadis, 2007).

This paper is about the UK regulatory methodology for major accident hazard (MAH) pipelines and a recent review which led to a programme of improvements. A number of reports (Chaplin, 2015a, 2015b, 2015c, 2015d) describe the review and required improvements. This paper describes the new overall fracture mechanics methodology and the comparison testing process carried out to determine that the implementation is fit for purpose.

The Health and Safety Executive (HSE) uses a fracture mechanics model, PIPINV3 (PIPeline INtegrity) (Chaplin, 2015a, 2015b, 2015c, 2015d), to calculate failure frequencies for major accident hazard (MAH) pipelines. The results are used in a pipeline risk assessment model to determine land-use planning (LUP) zones around the pipeline. The LUP zones are used by HSE to provide guidance to local planning authorities in Great Britain on whether to grant planning permission to proposed developments near a pipeline, or to assess the risk of harm to the public from potential modifications to existing pipelines, and/or for proposed new pipelines.

Four failure modes are considered (external corrosion, mechanical failures, natural ground movement/other failures and third party activity (TPA)); the first three of which are assessed using historical, operational experience data. Third party activity (TPA), which is often the major cause of failure, utilises a fracture mechanics approach.

PIPIN was originally developed in the late 1990s by WS Atkins (Linkens, Shetty, & Bilo, 1998) using a FORM/SORM (First/Second Order Reliability Method) (Shetty, Gierlinski, Liew, & Mitchell, 1996; Shetty, Gierlinski, Smith, & Stahl, 1997; Thoft-Christensen & Baker, 1982) approach. The model failed to converge on occasions and the decision was made to rewrite the model to incorporate a Monte Carlo solution method. The science behind the model was independently reviewed and updated as required based on the recommendations from the review (Francis, 2009). The review recommended modifications to some of the equations and a revised correlation to consider micro-cracks that can form at the base of a dent. The modifications to the science have been detailed previously (Chaplin, 2015b). All the data feeding into the model was also updated as part of the redevelopment. The revised model has been called PIPINV3 and is now used by HSE to calculate failure frequencies for major accident hazard pipelines.

This paper details all of the science contained within the PIPINV3 model, in addition to the science modifications that have been described previously (Chaplin, 2015b). Specific details of the change to a Monte Carlo solution method and the data updates are not covered. The paper compares the results of this new model against a previous version where the Monte Carlo solution method is used but none of the science changes has been incorporated. This comparison is required by HSE to ensure that the model is fit for purpose.

PIPIN overview

The fracture mechanics model within PIPINV3 considers failures of pipelines due to plastic collapse or fracture. Plastic collapse can occur when a section of the pipe wall is inadvertently removed, normally due to some machinery impacting the pipeline. This leads to a gouge or a gouge associated with a dent, which can result in a through wall failure initially giving rise to a leak. In either case, an initial, unstable leak can lead to a rupture of the pipeline (an unstable leak occurs when the defect is above a critical defect length, at which point the size of the leak can increase and result in a rupture). HSE define pipeline rupture as any hole exceeding 110 mm in diameter, which means that stable leaks above this size are also classed as ruptures (a stable leak does not increase in size as its defect length is below the critical defect length).

Figure 1 illustrates a gouge: the depth of the gouge is given by *d* and the pipeline thickness is given by *t*. An example of a dent and gouge is given in Figure 2, where the gouge depth is again denoted by *d* and the dent depth by *ddent*. The gouge semi-length is denoted by *c* for both the gouge and the dent and gouge examples, as shown in Figure 3.

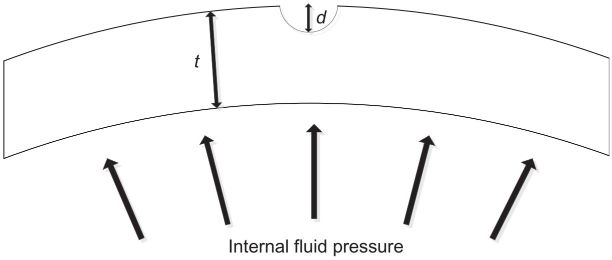

Figure 1. Illustration of a gouge in the wall of the pipeline.

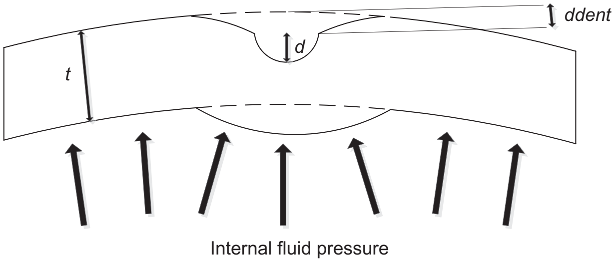

Figure 2. Illustration of a dent and gouge in the wall of the pipeline.

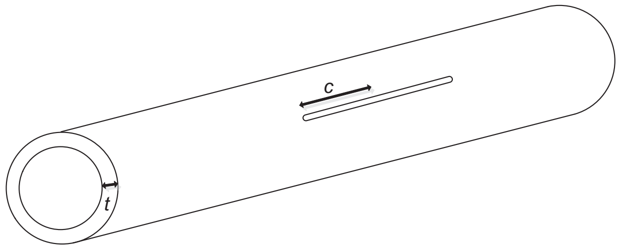

Figure 3. Illustration of the gouge semi-length in the wall of the pipeline.

PIPINV3 contains three fracture mechanics models:

- a gouge model that models the plastic collapse of the pipeline using either gouge data or dent-gouge data;
- a dent-gouge model that models failure of the pipeline by fracture; and
- a rupture model that models the likelihood of a leak leading to a rupture, resulting from either of the above failures.

The gouge model and rupture model are run twice, once to model the plastic collapse of the pipeline from a gouge, using gouge data, and once to model the plastic collapse of the pipeline from a gouge associated with a dent, using dent-gouge data.

A Monte Carlo solution method is used to calculate a probability of failure from each of these five submodels, given a single set of inputs. The individual probabilities calculated from each submodel are combined to produce failure frequencies for three representative hole sizes in the pipeline and for a pipeline rupture.

Gouge model

The equations for the gouge model are based on an approximate solution that was shown to represent experimental data for 36 machined notches with a reasonable degree of accuracy (Kiefner, Maxey, Eiber, & Duffy, 1973). The solution was based on the remaining ligament thickness which is scaled to take account of bulging using the Folias bulging magnification factor, $M(\rho)$, given by $M(\rho) = \left(1 + 1.61\rho^2\right)^{0.5}$ where the dimensionless gouge length, ρ, is dependent on the gouge semi-length, c (mm), the pipeline average radius, R (mm), and the pipeline thickness, t (mm) i.e. $\rho = c/(Rt)^{0.5}$. The Folias bulging magnification factor is used to take account of bulging in the remaining thickness of pipeline after a gouge has occurred.

The limiting hoop stress, i.e. the stress in the circumferential direction, σ_L (MPa), is given by:

$$\sigma_L = \frac{\sigma_y\left(1-\frac{d}{t}\right)}{1-\left(\frac{d}{t}\right)\frac{1}{M(\rho)}} \tag{1}$$

where σ_y is the yield stress (MPa).

A failure is assumed to occur if:

$$L_r = \frac{\sigma_h}{\sigma_L} > \frac{\sigma_u + \sigma_y}{2\sigma_y} \tag{2}$$

Where L_r is the ratio of the pressure hoop stress to the limiting hoop stress, σ_h is the pressure hoop stress (MPa) and σ_u is the tensile stress (MPa).

The distributions applied to the gouge depth and gouge semi-length are different, depending on whether a gouge or a dent-gouge is being considered. The gouge depth and semi-length are assumed to follow a Weibull distribution when modelling a gouge only. The Weibull distribution is a statistical distribution commonly used to model failure in engineering applications. When a dent is also formed, the gouge depth follows a Weibull distribution and the gouge semi-length follows a lognormal distribution when modelling the plastic collapse of the pipeline. In all cases, the parameters for the distributions have been derived from an analysis of historical fault data in the UK (Chaplin, 2015c).

Dent-gouge model

If a dent is formed in the pipeline, then through-wall bending occurs in the region of the dent leading to an increase in the tensile stresses on the outer surface of the pipeline. This will significantly increase the probability that the pipeline will fail, and, in the case where a gouge also occurs, can lead to micro-cracks opening at the base of the gouge.

The dent depth, *ddent* (mm), is given by the empirical formula (Linkens et al., 1998):

$$ddent = \left(\frac{Fdent}{0.49\sqrt{Res}}\right)^{2.38} \tag{3}$$

where *Fdent* is the dent impact force (kN) and *Res* is given by:

$$Res = \sqrt{80\sigma_y t}\left(t + \frac{0.7PD}{\sigma_u}\right) \tag{4}$$

where P is the internal pressure (MPa), D is the pipeline external diameter (mm), σ_y is the yield stress (MPa) and t is the pipeline thickness (mm).

The impact force is assumed to follow a lognormal distribution where parameters have been determined by analysing historical UK fault data (Chaplin, 2015c).

In order to determine if a pipeline fails, two tests are undertaken. The first assesses whether the pipeline is close to plastic collapse and the second whether it is close to fracture. To determine whether the pipeline fails due to plastic collapse, the ratio of the pressure hoop stress to the limiting hoop stress (L_r) needs to be considered as for the gouge model i.e. a failure occurs if:

$$L_r = \frac{\sigma_h}{\sigma_L} > \frac{\sigma_u + \sigma_y}{2\sigma_y} \tag{5}$$

where the pressure hoop stress, σ_h (MPa), is given by $\sigma_h = PR/t$ and the limiting hoop stress, σ_L (MPa), is given by $\sigma_L = \sigma_y(1-d/t)$. R is the average pipeline radius (mm) and d is the depth of the gouge associated with the dent (mm).

The limiting hoop stress does not require an additional bulging factor, as in the case of the gouge, as the dented region does not behave as a plain cylinder. It is, therefore, based only on the remaining ligament thickness.

As the first stage in the process to determine whether or not the pipeline fails due to fracture, the membrane stress at the dent, σ_m (MPa), is calculated by $\sigma_m = \sigma_h(1-0.9ddent/R)$. The bending stress, σ_b (MPa), is given by $\sigma_b = 10.2\sigma_h ddent/2t$.

Micro-cracks are assumed to be present in the regions of local tensile stresses and they can contribute to the failure of the pipeline wall. The following correlation (Chaplin, 2015b) for the micro-crack depth, a (mm), has been derived by fitting predictions from a simplified version of the model to results from 124 British Gas tests (Jones, 1982):

$$a = 3.5518e^{-0.0013\left(\frac{P(D+ddent)}{2(t+d)}\right)} \tag{6}$$

The primary, K_{1p}, and secondary, K_{1s}, stress intensity factors (MPa $m^{0.5}$) are given by:

$$K_{1p} = K_{1m} = Y_m SCF \sigma_m \sqrt{\frac{\pi a}{1000}} \tag{7}$$

$$K_{1s} = K_{1b} = Y_b SCF \sigma_b \sqrt{\frac{\pi a}{1000}} \tag{8}$$

where K_{1m} is the membrane stress intensity factor (MPa $m^{0.5}$), K_{1b} is the bending stress intensity factor (MPa $m^{0.5}$), and SCF is the stress concentration factor, which has been assumed to be 3. This is a standard value assuming the crack is located at the bottom of a semi-circular gouge (Linkens, 1997).

Y_m is a membrane factor;

$$Y_m = \left(1.12 - 0.23\frac{a}{t} + 10.6\left(\frac{a}{t}\right)^2 - 21.7\left(\frac{a}{t}\right)^3 + 30.4\left(\frac{a}{t}\right)^4\right) \tag{9}$$

and Y_b is a bending factor;

$$Y_b = \left(1.12 - 1.39\frac{a}{t} + 7.32\left(\frac{a}{t}\right)^2 - 13.1\left(\frac{a}{t}\right)^3 + 14.0\left(\frac{a}{t}\right)^4\right) \tag{10}$$

The primary stresses act on the body as a whole and are due to internal pressure and external loads. The secondary stresses are self-balancing. How the primary and secondary stresses interact depends on the level of plasticity in the substance. The higher the L_r ratio, as given in Equation 5, and therefore, the higher the likelihood of significant plasticity, the less impact the secondary stresses will have, as local yielding may partially relieve these stresses.

A comparison is made with the R6 Rev. 3 fracture assessment curve (Central Electricity Generating Board [CEGB], 1976). This is a curve such that, if a point lies above it, then the pipeline has failed i.e. the pipeline fails if:

$$K_r > \left(1 - 0.14L_r^2\right)\left(0.3 + 0.7e^{-0.65L_r^6}\right) \tag{11}$$

where K_r is the fracture ratio due to the applied primary and secondary stresses.

The fracture ratio is calculated as $K_r = K_{rp} + K_{rs}$ where K_{rp} is the primary fracture ratio associated with membrane stresses given by $K_{rp} = K_{1p}/K_{1c}$. K_{rs} is the secondary fracture ratio associated with bending stresses, $K_{rs} = K_{1s}/K_{1c} + \rho$.

K_{1c} is the fracture toughness (MPa $m^{0.5}$) and can also be referred to as the critical stress intensity factor. It reflects a material's ability to resist fracture and is an empirical relationship derived from Charpy V-notch impact tests (Kiefner et al., 1973), which determine the amount of energy absorbed by a material during fracture. $K_{1c} = \sqrt{12CVN \times E \times 0.08334/A_c}$. CVN is the 2/3 Charpy energy (J), E is Young's modulus (GPa), A_c is the Area of Charpy (mm^2), assumed to be 66.7 mm^2, and ρ is the plasticity correction factor which is calculated as:

$$\begin{aligned} &\mathit{If}\ L_r \le 0.8 && \rho = \rho_1 \\ &\mathit{If}\ 0.8 < L_r < 1.05 && \rho = 4\rho_1(1.05 - L_r) \\ &\mathit{If}\ L_r \ge 1.05 && \rho = 0 \end{aligned} \tag{12}$$

where ρ_1 is calculated as:

$$\begin{aligned} &\mathit{If}\ x < 4.0 && \rho_1(x) = 0.1x^{0.714} - 0.007x^2 + 0.00003x^5 \\ &\mathit{If}\ x \ge 4.0 && \rho_1(x) = 0.188 \end{aligned} \tag{13}$$

and

$$x = K_{1s}/\left(K_{1p}/L_r\right).$$

Rupture model

The rupture model within PIPINV3 calculates the conditional probability of a rupture given a through wall crack caused by either a gouge or a dent-gouge. The same model is used for both scenarios as ruptures are dominated by the average stress through the wall thickness, which is assumed to be approximately the same in both cases. It is further assumed that surface gouges or dents will extend through the wall before propagating along the pipeline length. A penetrating defect, therefore, precedes a long-running rupture. This has been modelled as a straight-fronted rectangular crack whose length is the same as the associated gouge.

The first stage of the rupture model is to calculate the Folias bulging factor, as for the gouge model, and the fracture toughness, as for the dent-gouge model. The limiting hoop stress, σ_L (MPa) is calculated as $\sigma_L = \sigma_y/M(\rho)$.

The ratio of the pressure hoop stress to the limiting hoop stress, L_r, is calculated as in the dent-gouge model (Equation 5), and the pipeline is assumed to have ruptured if the inequality in Equation 5 holds true. The pipeline is also assumed to fail if the R6 Rev. 3 fracture assessment curve (CEGB, 1976) is exceeded (Equation 11). In this model, this indicates that a rupture in the pipeline has occurred. In this case, K_r (MPa m$^{0.5}$), is calculated by $K_r = K_1/K_{1c}$ where K_{1c} is the fracture toughness and is calculated as in the dent-gouge model and K_1 is the stress intensity factor $K_1 = \sigma_h M(\rho)\sqrt{\pi c/1000}$.

The critical crack length, l_{2c} (mm), is used as part of the calculations to apportion the failures to the different representative hole sizes modelled. The critical crack length is calculated within the rupture model for each iteration of the model. It is assumed that when the value of K_r lies on the R6 Rev. 3 fracture assessment curve (CEGB, 1976), K_1 is at its critical value (K_{1crit}). At this point, the value of c, the gouge semi-length, within the equation for K_1 is taken to be the critical crack semi-length, l_c. As $K_1 = K_{1crit}$ where K_{1crit} is K_{ic} in the dent-gouge model, rearranging the equations leads to a cubic in l_c, which has one real root:

$$\frac{1.61 l_c^3}{Rt} + l_c - \frac{1000 K_{1crit}^2}{\pi \sigma_h^2} = 0 \tag{14}$$

The value of l_c must be multiplied by 2 to derive the critical crack length, l_{2c}. The mean critical crack length value is calculated across all the iterations carried out in the Monte Carlo simulations. Two values are calculated for each iteration, one crack length for gouges and one crack length for dent-gouges.

Failure frequency calculation

The failure probabilities from each of the fracture mechanics models are combined with incident frequencies (i.e. the frequency with which each event occurs) and probabilities of each representative hole size to produce overall failure frequencies for each representative hole size. HSE considers three representative hole sizes for pipelines and a pipeline rupture:

- Pinhole: $\leq$25 mm diameter;
- Small hole: $>$25 mm and $\leq$75 mm diameter;
- Large hole: $>$75 mm and $\leq$110 mm diameter; and
- Rupture: $>$110 mm diameter.

The holes represent the surface area of a puncture. In reality, the hole could be elongated rather than a perfect circle.

The representative hole sizes are converted into equivalent defect lengths, L (mm), which are assumed to be a function of the hole size normalised as a percentage of the pipeline internal cross-sectional area (Chaplin, 2015a):

$$L = (Dt)^{1/2}\left(\frac{A}{7.548 \times 10^{-4}}\right)^{\frac{1}{3.706}} \tag{15}$$

where A is the normalised hole area (i.e. the hole area/pipeline internal cross-sectional area expressed as a percentage).

As the gouge length is assumed to be distributed according to a Weibull distribution, the probability of a gouge length in a certain defect length range (corresponding to the defect lengths required to create holes of the representative sizes used in the model) can be calculated from the Weibull cumulative distribution, using the gouge length Weibull parameters, i.e.

$$P_{gl}(l) = 1 - e^{\left(-\left(\frac{l}{\beta}\right)^{\alpha}\right)} \tag{16}$$

where $P_{gl}(l)$ is the probability of a gouge length between 0 and l mm. α and β are the parameters for the Weibull distribution.

Similarly, for dent-gouges, the gouge length when a gouge is associated with a dent is distributed according to a lognormal distribution. In this case, the probability of a hole in a certain diameter range is calculated using the cumulative lognormal distribution:

$$P_{gl}(l) = \frac{1}{2} erfc\left(-\frac{\ln l - \mu}{\sigma\sqrt{2}}\right) \tag{17}$$

where μ and σ are the mean and standard deviation of the variable's natural logarithm, which, by definition, is normally distributed, and *erfc* is the complementary error function.

The probabilities of each of HSE's representative hole size ranges can be calculated by using appropriate values of l in Equations 16 and 17. For small holes, the probability of a hole $\leq 25\,mm$ is subtracted from that of a hole $\leq 75\,mm$ to obtain the required range. Large holes are calculated similarly. For ruptures, the probability of a hole $\leq 110\,mm$ is subtracted from a probability $=1$.

The individual probabilities from the fracture mechanics models can then be combined with the likelihoods of these incidents occurring. The resulting frequencies calculated are split into failure frequencies for each representative hole size. Ruptures can occur as a result of an unstable leak or of a stable leak that leads to a hole size greater than 110 mm. In both cases, the cause can either be a gouge or a dent-gouge. The failure frequency of a rupture is given by (Chaplin, 2015b):

$$\begin{aligned} Failure_r = & \left[f_g \times P_g \times P_{gr}\right] + \left[f_{dg} \times (P_d + P_{dg}) \times P_{dgr}\right] \\ & + \left[f_g \times P_g \times (wg_{>110\,mm} - P_{gr}) \times H\left(l_{2cg} - l_{110\,mm}\right)\right] \\ & + \left[f_{dg} \times (P_d + P_{dg}) \times \left(wdg_{>110\,mm} - P_{dgr}\right) \times H(l_{2cd} - l_{110\,mm})\right] \end{aligned} \quad (18)$$

where:

- l_{2cx} is the mean critical crack length (mm) across all iterations of the model where x is a gouge (g) or a dent-gouge (d);
- $l_{110\,mm}$ is the equivalent length for a hole of diameter 110 mm;
- f_x is the incident frequency, or strike rate, calculated from historical incident data, where x represents a gouge (g) or dent-gouge (dg);
- P_{xr} is the probability of a rupture where x is a gouge (g) or dent-gouge (dg);
- P_x is the probability of a failure where x is a gouge (g), a dent (d) or a dent-gouge (dg);
- $wx_{>110\,mm}$ is the probability of a hole size greater than 110 mm diameter where x is a gouge (g) or dent-gouge (dg); and
- H is the Heaviside step function, which is 0 if $l_{110\,mm}$ is greater than l_{cx}, and 1 otherwise.

The first two terms in Equation 18 capture unstable leaks from either a gouge or a dent-gouge that lead to a rupture. The remaining two terms capture all stable leaks that lead to holes greater than 110 mm in diameter, from either a gouge or a dent-gouge.

It may be more appropriate to apply a Cauchy statistical distribution to determine the critical crack length, rather than using the mean value calculated from the Monte Carlo simulation. A Cauchy statistical distribution would entail using the median value instead of the mean value to calculate the critical crack length. Further investigations into the use of this distribution have indicated that the differences identified between the mean and median values calculated for the critical crack length are of the order of 10%. It has been found that the critical crack length is lower than the equivalent length for a hole of diameter 110 mm in most cases, meaning that the last two terms in Equation 18 are usually not required. Calculating the median value is more computationally intensive than calculating the mean. This suggests that there would be no benefit in moving to the median value, but there would be a significant computational cost incurred. The mean value is therefore used in preference to the median in the calculation of the critical crack length within the PIPINV3 model (Chaplin, 2015b).

The failure frequency for the representative holes is given by:

$$\begin{aligned} Failure_h = & \left[f_g \times wg_h \times P_g \times (1 - P_{gr})\right] \\ & + \left[f_{dg} \times wdg_h \times P_d \times (1 - P_{dr})\right] \\ & + \left[f_{dg} \times wdg_h \times P_{dg} \times (1 - P_{dr})\right] \end{aligned} \tag{19}$$

where wx_h is the probability of a hole size, h (pinhole, small hole, large hole), where x is a gouge (g) or dent-gouge (dg).

The first and third terms in Equation 19 represent stable leaks from plastic failures of the pipeline from either a gouge or a dent-gouge. The second term represents stable leaks from fracture of the pipeline caused by a dent.

Model comparison

PIPINV3 is the revised version of the PIPIN model with a Monte Carlo solution method incorporated, with modified science and with updated historical data applied to the model. The previous sections have described all the science within the model, which incorporates the modifications from the earlier model. PIPINV3 has been compared to the MCPIPIN version of the model. MCPIPIN replicates the original version of the PIPIN model with no science or data changes but using a Monte Carlo solution method in preference to the FORM/SORM (First/Second Order Reliability Method) solution method that was used in the original PIPIN model. A test set of data for 584 pipelines from the UK natural gas pipeline dataset have been run through both models and the results from both models compared.

The failure frequencies calculated for each of the test data pipelines using PIPINV3 have been divided by those using the MCPIPIN model to obtain ratios to express how results have changed from the introduction of the new science and data. The mean, maximum and minimum values of these failure frequency comparison ratios derived from the testing have been calculated, along with the standard deviation for these calculated ratios. The ratios for third party activity (TPA) only are shown in Table 1 and the ratios where failures due to mechanical, corrosion and natural ground movement/other causes are included are shown in Table 2. The failure frequencies for all causes other than TPA are based on historical data only.

The results indicate that there is an overall increase in the predicted failure frequencies calculated for pinholes for third party activity (TPA) from the changes made in the science and data for PIPINV3. The predicted failure frequencies for the other representative hole sizes decrease for all scenarios modelled when considering TPA only.

When the other failure causes are considered in conjunction with TPA, the failure frequencies calculated are reduced for all of the 584 pipelines tested in the data set for representative small holes and large holes. The failure frequencies are reduced, on average, for pinholes and ruptures when considering all failure modes, although there are some pipelines that see an increase in the failure frequency calculated for these representative hole sizes.

PIPINV3 is an input to HSE's pipeline risk assessment model, MISHAP12 (Chaplin, 2015e). MISHAP12 is used to determine the Land Use Planning (LUP) zone distances around pipelines to allow HSE to provide advice to local planning authorities. The data set of 584 pipelines were run through MISHAP12, using the failure frequencies generated from PIPINV3. The resulting Land Use Planning (LUP) zone sizes output by MISHAP12 were compared with those output by MISHAP12 when using failure frequencies from the original FORM/SORM version of PIPIN.

The LUP zones calculated for each of the test data pipelines using the failure frequencies from PIPINV3 have been divided by those using the failure frequencies from the original version of PIPIN. The mean, maximum and minimum values of these LUP zone comparison ratios derived from the testing have been calculated, along with the standard deviation for these calculated ratios. The results of the comparison are shown in Table 3. The zones are defined as a risk of receiving a HSE dangerous dose of greater than 10 cpm/yr (chances per million per year) for the inner zone, between 1 cpm/yr and 10 cpm/yr for the middle zone and between 0.3 cpm/yr and 1 cpm/yr for the outer zone.

Table 1. Summary statistics of the comparison of PIPINV3 with MCPIPIN: TPA only (PIPINV3 failure frequencies)/(MCPIPIN failure frequencies) for the test set of 584 pipelines.

Hole size	Pin	Small	Large	Rupture
Mean	1.46	0.70	0.66	0.60
Minimum	0.05	0.03	0.03	0.04
Maximum	2.06	0.99	0.99	0.91
Standard deviation	0.43	0.20	0.17	0.15

Table 2. Summary statistics of the comparison of PIPINV3 with MCPIPIN: total frequencies (PIPINV3 failure frequencies)/(MCPIPIN failure frequencies) for the test set of 584 pipelines.

Hole size	Pin	Small	Large	Rupture
Mean	0.67	0.50	0.44	0.73
Minimum	0.12	0.26	0.18	0.27
Maximum	2.58	0.81	0.76	1.20
Standard deviation	0.46	0.16	0.17	0.14

Table 3. Summary statistics of the comparison of PIPINV3 with PIPIN: LUP zones (PIPINV3)/(original PIPIN) for the test set of 584 pipelines.

	Inner zone	Middle zone	Outer zone
Mean	1.00	0.82	0.90
Maximum	1.00	1.00	1.06
Minimum	0.48	0.05	0.10
Standard deviation	0.03	0.22	0.12

The results indicate that the inner and middle zones remained the same or were reduced in size in all cases, and the outer zone was reduced in size for most of the pipelines when PIPINV3 was used to generate the failure frequencies. Reducing the LUP zones can impact on the advice given by HSE for proposed developments in the vicinity of the pipelines, or on proposed modifications to the pipeline itself (Health and Safety Executive [HSE], website).

Conclusions

The science within PIPIN has been updated to ensure that the advice given by HSE to local planning authorities is based on current scientific knowledge. The additional work to incorporate a Monte Carlo solution method, which is not detailed here, has solved the convergence issues seen with the original FORM/SORM code. The inclusion of more up-to-date data, which is not detailed here, has ensured that HSE's advice is based on relevant data. The combined effects of all the modifications lead to either no change or a reduction in the size of the calculated LUP zones in most cases.

Disclaimer

The contents, including any opinions and/or conclusions expressed in this publication, are those of the authors alone and do not necessarily reflect HSE policy.

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Nomenclature

A	normalised hole area
A_c	area of Charpy (mm^2)
a	micro-crack depth (mm)
CVN	2/3 Charpy energy (J)
c	gouge semi-length (mm)
D	pipeline external diameter (mm)
d	gouge depth (mm)
$ddent$	dent depth (mm)
$Fdent$	dent force (kN)
E	Young's modulus (210,000 MPa)
$erfc$	complementary error function
f_{dg}	dent-gouge incident frequency
f_g	gouge incident frequency
K_1	stress intensity factor (MPa $\sqrt{m}$)
K_{1b}	bending stress intensity factor (MPa $\sqrt{m}$)
K_{1c}	fracture toughness (MPa $\sqrt{m}$)
K_{1crit}	critical value of the stress intensity factor (MPa $\sqrt{m}$)
K_{1m}	membrane stress intensity factor (MPa $\sqrt{m}$)
K_{1p}	primary stress intensity factor (MPa $\sqrt{m}$)
K_{1s}	secondary stress intensity factor (MPa $\sqrt{m}$)
K_r	fracture ratio due to the applied primary and secondary stresses
K_{rp}	primary fracture ratio associated with membrane stresses
K_{rs}	secondary fracture ratio associated with bending stresses
L_r	ratio of pressure hoop stress to the limiting hoop stress
l	defect length (mm)
l_{110mm}	equivalent length for a hole of diameter 110 mm (mm)
l_c	critical crack semi-length (mm)
l_{2c}	critical crack length (mm)
$M(\rho)$	Folias bulging magnification factor
P	internal pressure (MPa)
P_d	probability of a failure due to a dent
P_{dg}	probability of a failure due to a dent-gouge
P_{dgr}	probability of a rupture due to a dent-gouge
P_g	probability of a failure due to a gouge
P_{gl} (l)	probability of a gouge length between 0 and l mm
P_{gr}	probability of a rupture due to a gouge
R	average pipeline radius (mm)
SCF	stress concentration factor, assumed to be 3
t	pipeline wall thickness (mm)
$wdg_{>110mm}$	probability of a hole size greater than 110 mm from a dent-gouge
wdg_h	probability of a hole size h from a dent-gouge
$wg_{>110mm}$	probability of a hole size greater than 110 mm from a gouge
wg_h	probability of a hole size h from a gouge
Y_b	bending factor
Y_m	membrane factor
α	Weibull distribution shape parameter

β	Weibull distribution scale parameter
μ	mean of a variable's natural logarithm
ρ	dimensionless gouge length or plasticity correction factor
σ	standard deviation of a variable's natural logarithm
σ_b	bending stress (MPa)
σ_h	pressure hoop stress (MPa)
σ_L	limiting hoop stress (MPa)
σ_m	membrane stress (MPa)
σ_u	tensile stress (MPa)
σ_y	yield stress (MPa)
FORM	First order reliability method
HSE	UK Health and Safety Executive
LUP	Land use planning
MAH	Major accident hazard
PIPIN	Pipeline Integrity model
QRA	Quantitative risk assessment
SORM	Second order reliability method
TPA	Third party activity
UKOPA	UK Onshore Pipeline Operators' Association

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Notes on contributor

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