RELIABILITY MODEL FOR UNDERGROUND GAS PIPELINES

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ABSTRACT

A model is constructed for the failure frequency of underground pipelines per kilometer year, as a function of pipe and environmental characteristics. The parameters in the model were quantified, with uncertainty, using historical data and structured expert judgment. Fifteen experts from institutes in The Netherlands, the United Kingdom, Italy, France, Germany, Belgium, Denmark and Canada participated in the study.

KEYWORDS

Underground pipeline, corrosion, third party interference, marked point process, uncertainty analysis, expert judgement, risk analysis.

INTRODUCTION

Many countries have invested extensively in underground gas pipelines in the 1960's and 1970's. As these pipes are approaching the age at which problems of corrosion are expected to appear with increasing frequency, these countries may be facing massive investment. Previous studies (see for example, Kiefner, Vieth & Feder (1990)) focused on developing ranking tools which provide qualitative indicators for prioritizing inspection and maintenance activities. Such tools perform well in some situations, in The Netherlands, however, qualitative ranking tools have not yielded sufficient discrimination to support inspection and maintenance decisions. The population of gas pipelines in The Netherlands is too homogeneous.

We model the *uncertainty in the failure frequency of gas pipelines* as a function of observable pipeline and environmental characteristics [4] Although extensive failure data is available, the data is not sufficient to quantify all parameters in the model. The effects of combinations of pipe and environmental characteristics on the failure frequency is uncertain and is assessed with expert judgment (Cooke (1991)). Fifteen experts participated in this study, from The Netherlands, Germany, Belgium, Denmark, The United Kingdom, Italy, France and Canada.

This article describes an on-going effort to upgrade the basis for decisions regarding inspection and replacement of underground pipelines. When values for the pipe and environmental characteristics are specified, the model yields an uncertainty distribution over the frequency per kilometer year of various damage types. The model was introduced in Cooke & Jager (1998). In this paper we briefly review the model, and compare the model predictions with data which has recently become available.

OVERVIEW OF MODELLING APPROACH

The failure probability of gas pipelines is modelled as the sum of a failure probability due to third party actions and a failure probability due to corrosion[5]:

$$\begin{aligned} &P\{\text{failure of gas pipelines/ km}\cdot\text{yr}\} = \\ &\quad P\{\text{direct leak due to 3rd parties/ km}\cdot\text{yr}\} + \\ &\quad P\{\text{failure due to corrosion/ km}\cdot\text{yr}\} \end{aligned} \tag{1}$$

Both terms on the right hand side will be expressed as functions of other uncertain quantities and parameters. The parameters will be assigned specific values in specific situations, the uncertain quantities are assigned subjective uncertainty distributions on the basis of expert assessments. This results in an uncertainty distribution over possible values of $P\{\text{failure of gas pipelines/km}\cdot\text{yr}\}$, conditional on the values of the known variables.

Failure due to corrosion requires damage to the pipe coating material, and (partial) failure of the cathodic and stray current protection systems. Damage to coating may come either from third parties or from the environment (Lukezich, Hancock & Yen (1992)). The overall model may be put in the form of a fault tree as shown in Figure 1.

Third party interference

The model described in detail in (Cooke and Jager 1998). Suffice to say here that the underlying probability model is a so-called "marked point process". For a given one kilometer section of

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[4] Following (Basalo (1992), Lukezich, Hancock & Yen (1992), Chaker & Palmer (1989)), these are: pipe wall thickness, pipe diameter, ground cover, coating, age of pipe (since last inspection), frequency of construction activity, frequency of drainage, pile driving, deep plowing, placing dam walls, percent of pipe under water table, percent of pipe exposed to fluctuating water table, percent of pipe exposed to heavy root growth, percent of pipe exposed to chemical contamination, soil type (sand, clay, peat), pH value of soil resistivity of soil presence of cathodic protection, number of rectifiers, frequency of inspection of rectifiers, presence of stray currents, number of bond sites.

[5] The model does not include stress corrosion cracking or hydrogen induced cracking, as these have not manifested themselves in The Netherlands. Damage to pipelines during construction and installation is not modelled. Low probability scenarios like earthquake and flood have not been modelled, and 'exotic' scenarios like sabotage, war, malfeasance and the like are neglected.

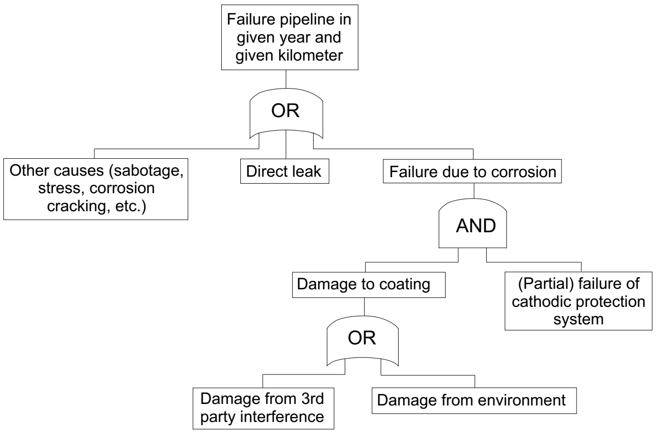


Figure 1: Fault tree for gas pipeline failure

pipe, third party activities (within 10 meters of the pipe) are represented as a Poisson process in time. Each dig-event is associated with a number of "marks"; i.e. random variables which assume values in each dig-event (Figure 2). For each 1 km pipe section, the following picture emerges:

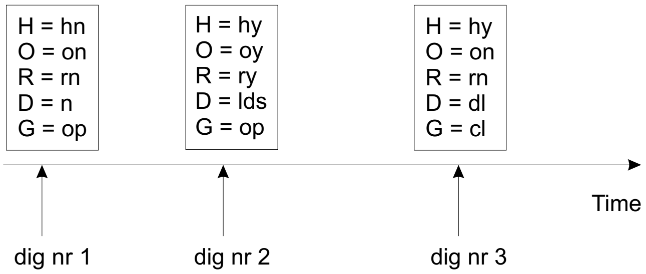


Figure 2: Digs as marked point process

On the first dig the pipe was not hit, hence the damage was none ($D = n$) and no repair was carried out ($R = rn$). The second dig was an open dig with oversight; small line damage occurred, but was repaired. The third dig was closed without oversight, the line was hit and resulted in a direct leak. By definition, repair was unable to prevent leak, hence $R = rn$.

Damage due to Environment

In dealing with damage to coating due to environmental factors per kilometer year, we adopt the frequency notation, as this frequency F can be larger than one. For both bitumen (bit) and polyethylene (pe) coatings, the probability of environmental damage depends on the pipe diameter (d), on the soil type (st) and on the percentage of the pipe exposed to fluctuating water table (wt_f). Bitumen coating is also sensitive to the proportion of the one-kilometer length exposed to tree roots (rt) and chemical contamination (ch). The effects of these factors are captured with a first order Taylor expansion whose linear terms $p_5, \ldots, p_{10}$ are assessed by experts.

$$\begin{aligned} F(bit) &= Fo(bit) + p_5 \cdot (d - d_0) + p_6 \cdot wt_f + p_7 \cdot rt + p_8 ch + st \cdot bit \qquad (2) \\ F(pe) &= Fo(pe) + p_9 \cdot (d - d_o) + p_{10} \cdot wt_f + st \cdot pe \qquad (3) \end{aligned}$$

Failure due to corrosion

The modelling of failure due to corrosion is more complicated than that of failure due to third parties. For details see (Cooke and Jager 1998). The corrosion rate is uncertain, but is assumed constant in time (Camitz & Vinka (1989)). For a pipeline to fail due to corrosion, two lines of defense must be breached. First the coating must be damaged, and second, depending on location, the cathodic or stray current protection system must not function as intended. Coating damage may be caused either by third party actions or by environmental factors.

Assuming that the coating has been breached, pit corrosion will reduce the pipe wall thickness until a critical value is reached, at which point the pipe fails. This critical wall thickness, that is the thickness at which failure occurs, is expressed as a critical fraction xc of the original wall thickness minus the pipe material removed during the damage event. xc depends on the pressure of the gas in the pipe line, and on the geometry of the pipe damage, and this relationship has been established by experiment. In this model, xc is introduced as a parameter whose value depends only on the damage type, thus we distinguish x_C, x_S and x_L for (only) coating damage, small and large pipe damage respectively. Coating damage is either caused by 3rd parties ($cd3$) or by the environment (cde). By repeatedly sampling values from all uncertain quantities, the distribution for the frequency per kilometer year of damage exceeding a fraction xc of the original wall thickness can be built up.

VALIDATION

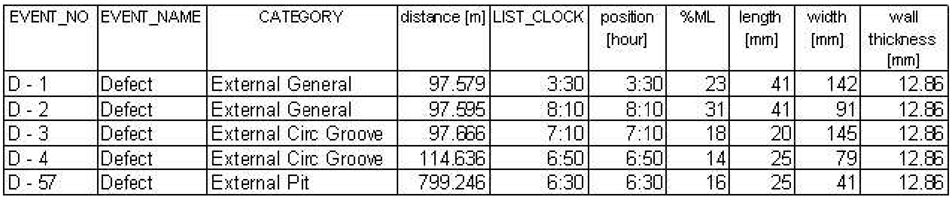
This model was originally developed in 1996 (see Cooke & Jager (1998)). In the last few years the Dutch gas company has launched a program of “intelligent pig runs”. An intelligent pig is a device that can be sent through a large diameter pipe to measure corrosion defects. These pig runs are quite accurate but also quite expensive. The gas company is interested in using these runs to calibrate the failure model, so that the model can be used to support the selection of pipes to be pigged in the future.

At present data from two pig runs are available. For each run, the data consists of a list of defects, their position on the pipe, and their depth. Run A covered 66 km of a gas pipeline with bitumen coating laid in sand in 1966, with average diameter of 12.45 inches at an average depth of 1.76 m. There were 65 incidents in which the removal of pipe material was at least 10 percent of the wall thickness.

Run B covered 84 km of a gas pipeline with bitumen coating laid in sand in 1965, with average diameter of 11.45 inches at an average depth of 1.87 m. There were 92 incidents in which the removal of pipe material was at least 10 percent of the wall thickness. A part of the data is included in this document (Figure 3).

The Laplace test was applied to each data set separately to test the hypothesis that the spatial inter-arrival times came from an exponential distribution, against the hypothesis that the data come from a non-homogeneous Poisson distribution. The Pipeline A data indicates a statistically significant spatial trend since 30% of observed corrosion appear in first 3km of the pipe (the pipe is 65 km long). This spatial clustering could not be explained and is not used in the further analysis. There was no significant ‘spatial trend’ in the Pipeline B data. A non-parametric Kolmogorov-Smirnov test was used to test the hypothesis that the spatial inter-arrival intervals for events removing at least 10 percent of pipe wall material came from the same distribution. The hypothesis was not rejected at the 5 percent level. Hence, no significant difference was found between the two data sets.

The model predicts the frequency of damage removing in excess of xc percent or the original wall thickness. By setting $xc = 10$ percent the 'failure frequency' output by the model corresponds to the frequency of corrosion events removing at least 10 percent of the pipe wall material. By setting xc successively equal to $10, 15, 20 \ldots 40$ percent we obtain 7 uncertainty distributions for the frequency per kilometer year of removing at least xc percent of the pipe wall material. For each value of xc, we retrieve the number of events removing at least xc percent of pipe wall material from the data. Dividing this number by the number of kilometer years, we obtain the empirical frequency per kilometer year of removing at least xc percent of pipe wall material. We then compare these empirical frequencies with the appropriate uncertainty distribution for these frequencies from the model. The results are shown in Figures 4 and 5. We see that the model places the observed frequencies well within the central mass of the respective uncertainty distributions.



EVENT_NO	EVENT_NAME	CATEGORY	distance [m]	LIST_CLOCK	position [hour]	%ML	length [mm]	width [mm]	wall thickness [mm]
D - 1	Defect	External General	97.579	3:30	3:30	23	41	142	12.86
D - 2	Defect	External General	97.595	8:10	8:10	31	41	91	12.86
D - 3	Defect	External Circ Groove	97.666	7:10	7:10	18	20	145	12.86
D - 4	Defect	External Circ Groove	114.636	6:50	6:50	14	25	79	12.86
D - 57	Defect	External Pit	799.246	6:30	6:30	16	25	41	12.86

Figure 3: The Gasunie data

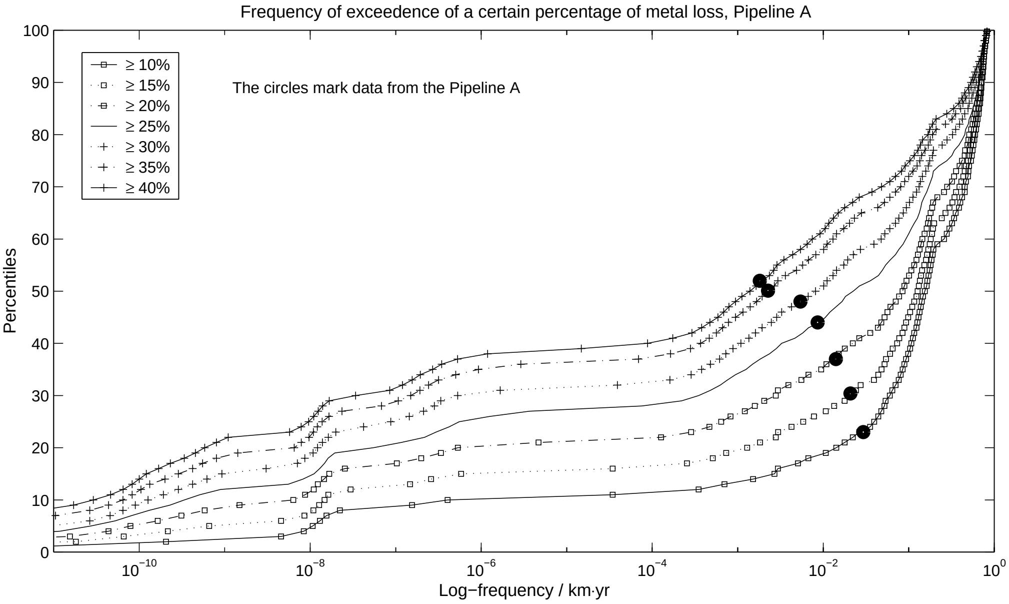


Figure 4: Uncertainty distributions and observed exceedence frequencies, pipe A

CONCLUSIONS

We conclude that the modelling of *uncertainty* in failure frequency of failure for underground gas pipelines proves reasonably successful in predicting observed frequencies of pipe damage. In spite of the fact that the uncertainties are very large, the central mass of the distribution of failure frequency is not so large, and the observed frequencies fall within this central mass. In the future observed data will be used to better calibrate the model, perhaps replacing expert uncertainties with measured values in some cases. The modelling of uncertainty has the additional advantage of enabling a sensitivity analysis to identify most effective ways of reducing uncertainty.

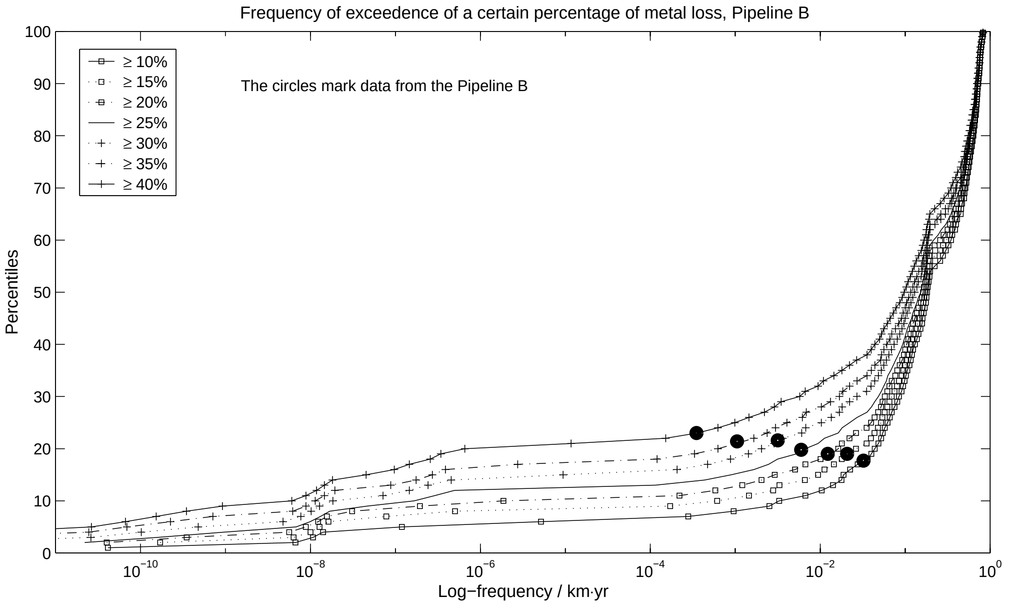


Figure 5: Uncertainty distributions and observed exceedence frequencies, pipe B

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