Analysis of spatial dependencies of corroding pipelines based on In-line (ILI) inspections

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Résumé :

La corrosion dans les pipelines terrestres suit un processus de dégradation qui est affecté par le sol environnant, l'âge du pipeline et l'état de la protection. Les exploitants de pipelines ont fréquemment recours à des inspections en ligne (ILI) pour détecter et mesurer, chaque 2 à 6 ans, qui sont ensuite utilisées pour évaluer la fiabilité des pipelines. Cependant, des nouveaux défauts peuvent apparaître entre deux inspections consécutives, ce qui affecte les prévisions initiales. Cet article évalue la distribution spatiale de ces défauts sur la base d'une étude de cas réelle afin de définir l'emplacement potentiel de nouveaux défauts recherchant des estimations de fiabilité précises. À cette fin, une hypothèse de hasard spatial complet est évaluée en fonction du critère du voisin le plus proche et de l'emplacement de l'effet par rapport aux joints de soudure.

Abstract:

Corrosion in onshore pipelines follows a degradation process that is affected by the surrounding soil, pipeline age, and the condition of the pipe protection. Pipeline operators frequently use In-Line (ILI) inspections to detect and measure metal loss at the wall thickness both at the inner and outer wall every 2 to 6 years, which are then used for evaluating pipe reliability. However, new defects can appear between consecutive inspections, which affects the initial predictions. This paper assesses the spatial distribution of these defects based on a real case study to define the potential location of new defects seeking for accurately reliability estimations. For this purpose, a Complete Spatial Randomness hypothesis is evaluated based on the Nearest Neighbor criterion and the effect location to the weld joints.

Keywords: Onshore pipelines; spatial variability; generation of defects; ILI inspections.

1 Introduction

Pipelines with corroding defects produce a space-dependent degradation (i.e., metal loss of the wall thickness) either at the inner or outer wall. This degradation is favored by the varied soil conditions surrounding the pipeline, the way the pipe is installed (e.g., underground, aboveground), and maintained (e.g., coatings, cathodic protection). For instance, several researchers have pointed out that soils with a higher concentration of chlorides, sulfates, acidic pH, and the presence of bacteria or fungi have a significant effect on external corrosion [1]. These defects may represent a Loss of Containment (LOC) and trigger considerable consequences to the surrounding people and environment; therefore, a space-dependent assessment to identify when and where maintenance should take place is required.

In this regard, some approaches have been proposed such as the one reported by Wang and co-workers [2]. They developed a framework to cluster defects depending on their corrosion rates, which are later used to estimate a space-dependent corrosion rate probability density. This approach considers defect measurements obtained from In-Line (ILI) inspections (commonly taken every 2 to 6 years), which provides a good perspective of the pipeline condition; however, new defects are expected to appear between these inspections due to the aggressive environment or miss-detections from the inspection tools [3]. For this purpose, some researchers have considered a Poisson Process to estimate the number of new defects and Monte Carlo simulations to define when they would appear [4, 5]. These approaches usually consider a uniformly random location [5], which may be conservative bearing in mind that corrosion clusters have been reported near welded joints [6].

The objective of this paper is to evaluate the assumption of the completely random location of corrosion defects based on two ILI measurements. The defects are analyzed using the distance between the nearest defects and the effect produced by the welding joints. The document is structured as follows: Section 2 describes the case study, Section 3 assess the number and location of corrosion defects near to the pipeline welds, and Section 4 evaluates the spatial randomness hypothesis with the nearest neighbor criterion. Finally, Section 5 presents some concluding remarks and some insights for further developments.

2 Case study description

The case study concerns two consecutive ILI measurements 2 years apart from an API 5LX52 pipeline 45km long with a height lying between 2560 to 2660m above the sea level. The pipeline is mainly located in a plain terrain (inclinations shorter than 7°), it crosses two mountain sections, a river, and two urban zones. The pipeline is composed of welded joints with an average length of 10.7m, and welded covers of 0.7m; it has a nominal wall thickness of 6.35mm and an external diameter of 273.1mm; and it is protected by a bituminous coating of coal tar and an impressed current cathodic protection (ICCP) system. Every reported corrosion defect has a specific depth, length, and width; its location is given based on the pipeline abscissa and a clock-position (12-hour analogy) as is illustrated in Figure 1.

The corrosion defects were classified following the categories reported by the Pipeline Operator Forum [3]. Table 1 depicts the distributions of these categories where it can be noticed that general and pitting corrosion cover a more significant number of defects (around 90% in both inspections and pipe walls), but there is still a relevant number of axial and circumferential grooving at the inner wall.

A MFL tool was implemented with a detection threshold of 10% of the wall thickness (t). The detection is not straightforward because false alarms or non-detected defects could also occur, which is why usually probabilities of detection and false alarm are considered. These probabilities were not contemplated in this paper because we did not have information on the defects below this reporting threshold, but we concentrated on defects with a depth $d \leq 15\%t$. The defects distribution along the abscissa (between two consecutive joints) is depicted in Figure 2; this figure also shows the different soils along the pipeline

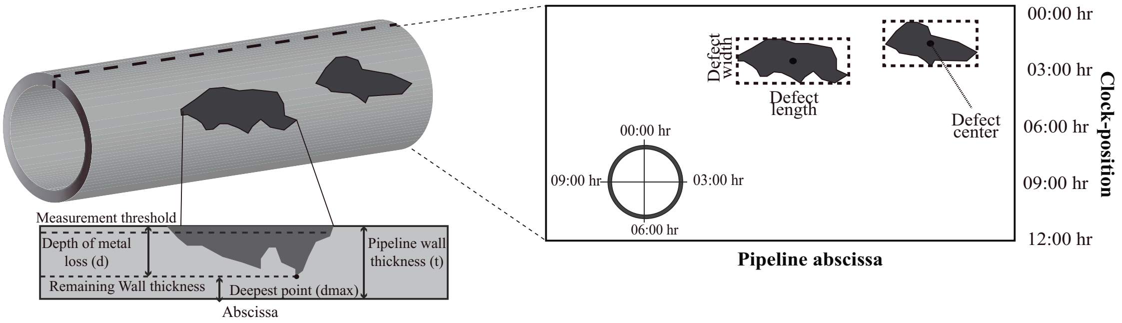

Figure 1: Scheme of the location of a corrosion defect. Modified from [3].

Table 1: Summary of corrosion defects along the abscissa

Parameter	Mean (Coefficient of Variation)			
	ILI-1 Inner wall	ILI-2 Inner wall	ILI-1 Outer wall	ILI-2 Outer wall
Average depth (%wt)	5.49 (0.26)	5.29 (0.27)	7.28 (0.49)	6.77 (0.46)
Maximum depth (%wt)	11.54 (0.21)	11.14 (0.19)	15.84 (0.46)	14.62 (0.43)
Length (mm)	26.07 (0.49)	26.07 (0.43)	28.07 (0.48)	27.37 (0.44)
Width (mm)	22.5 (0.40)	25.92 (0.53)	28.81 (0.67)	32.60 (0.75)
Number of defects	23708	43399	2862	4264

Category	Number of defects (% Total defects)			
	ILI-1 Inner wall	ILI-2 Inner wall	ILI-1 Outer wall	ILI-2 Outer wall
General	2007 (8%)	5766 (13%)	515 (18%)	891 (21%)
Pitting	19551 (82%)	34460 (79%)	2116 (74%)	2997 (70%)
Axial Grooving	1920 (8%)	2007 (5%)	164 (6%)	125 (3%)
Circumferential Grooving	230 (1%)	1166 (3%)	67 (2%)	271 (6%)

route. The location of new defects depends on the type of soil and particular features, for instance, near the 33th kilometer where a great amount of external corrosion is reported due to a river-crossing.

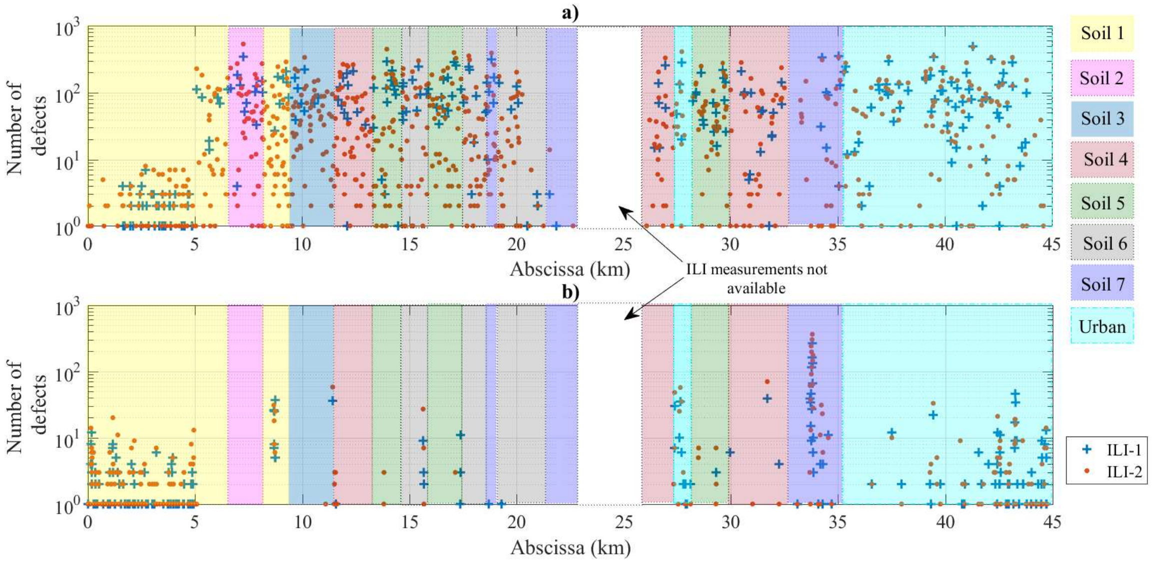

Figure 2: Number of newly defects per joint along the abscissa at the a) inner and b) outer wall

3 Effect of pipeline welds in corrosion defects

A welding process produces a fusion zone with high tension near to the yield strength, and residual tension in each side of the weld that is known as a Heat-Affected-Zone (HAZ) [7] as it is illustrated in Figure 3. Pipe joints are susceptible to failure at welding joints due to residual stresses that reduce the pipeline toughness and ductility, which in turn, increase the possibility of formation of cracks [7]. These cracks may occur in the HAZ zone and the weld root or toe [8]. Besides residual stresses from the welding process, joints welds have been experienced different forms of corrosion [9], especially near to the HAZ areas [6, 10]; i.e., where the base metal has been heated but not melted, and solid-state micro-structural changes were obtained [9]. This selective corrosion occurs because HAZ zones are less noble than the parental (base) metal due to possible galvanic couples of the fusion zone with its vicinity [9].

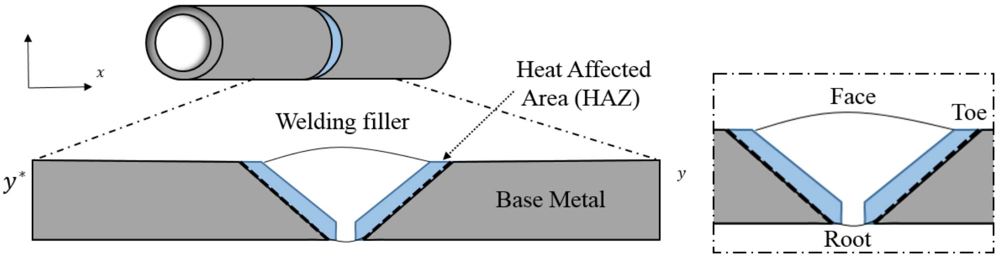

Figure 3: Pipeline weld scheme.

Considering that ILI inspections provide the location of these joints, the distance to the nearest joint was estimated every 500m. Defects in the external wall tend to be located within 1 to 2 m from the pipeline welds. There are 19 segments (21% of the pipeline) for ILI1-Ext that are clustered exclusively at this separation from the weld joints. For the inner wall, the distribution is more homogeneous, but there are some segments like the kilometers 2, 3.5, 5, 6, 22, and 36.5 that have near 50% defects within 1 to 2 meters away from the pipe joints. Similar distributions between the two inspections were obtained with more scatter for the external wall, which is due to segments with a low number of defects and possible repairs near the weld joints (e.g., 6.5km, 8.5km, and 18km).

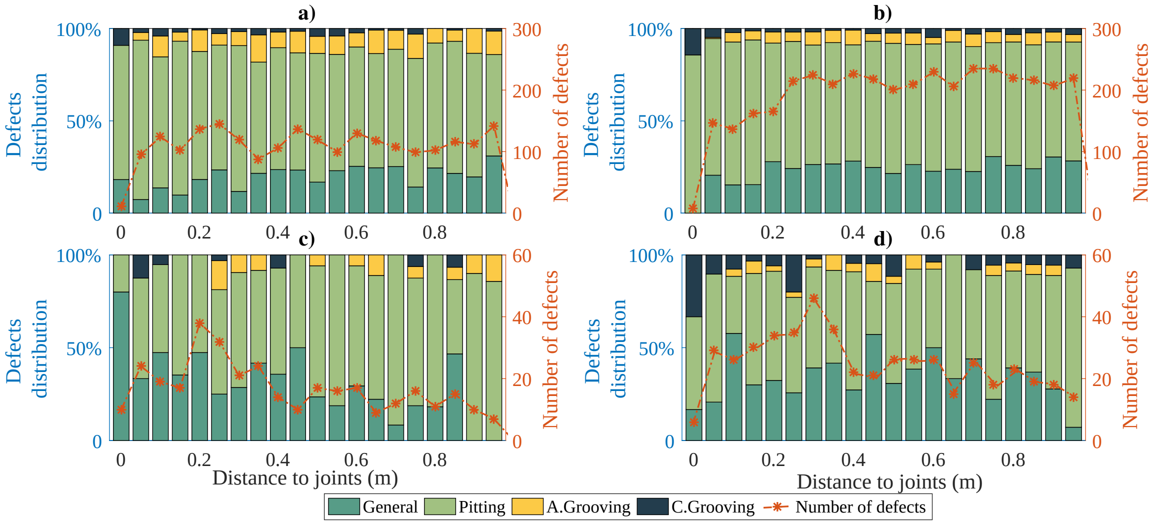

Figure 4: Number of defects 1m of the joint welds for a) ILI run-1's inner wall, b) ILI run-2's inner wall, c) ILI run-1's outer wall, and d) ILI run-2's outer wall.

The size of the HAZ zone depends on different factors including the material welded, the type of welding, welding time, the welding temperature, and the cooling efficiency [11]. The HAZ is not homogeneous but based on experimental results it can be assumed that it has a length shorter than 10cm [11], so a deeper analysis was done from defects up to 1m apart of weld joints.

The number of defects was determined every 0.05 m for each pipeline wall and ILI inspection as shown in Figure 4. This figure also depicts the defects distribution among general corrosion, pitting, axial and circumferential grooving for each of the obtained segments. This figure shows that the fusion zones (bar placed at $0m$) have the lowest number of defects in each case and the HAZ zone (which starts in the second bar) is significantly higher. Besides, this figure suggests that pitting corrosion tend to be located near weld joint in a more significant proportion than general corrosion or axial (circumferential) grooving; this result was pointed out also by Chaves & Melchers [10].

4 Spatial Randomness hypothesis testing

A Complete Spatial Randomness (CSR) is commonly assumed for the generation of new defects. This assumption establishes that a number of defects n are located uniformly in a domain $\mathcal{D}$, which can be imposed (Binomial process) or it may follow a realization of a Poisson distribution (Poisson process). In both cases, a intensity λ related to the mean number of defects per unit area is considered, which is assumed constant along $\mathcal{D}$, i.e., under a first-order stationarity using the estimator $\hat{\lambda} = n/Area(\mathcal{D})$. This assumption would be evaluated based on the nearest distance of the defects $\{d^i_{NN}, i = 1, \ldots, n\}$. Denote d_{obs} as the mean nearest distance obtained from the observed defects ($d_{obs} = \frac{1}{n}\sum_{i=1}^{n} d^i_{NN}$), and d_{exp} as the expected distance under CSR ($d_{exp} = \frac{1}{2\sqrt{\lambda}}$). Also, define the NN ratio r^{NN} as $r^{NN} = d_{obs}/d_{exp}$. According to this CSR test, if $r < 1$, then the events tend to be clustered; if $r \approx 1$, then the events are located randomly, and otherwise the events tend to be dispersed. This ratio was also obtained using a simulation approximation based on a Binomial processes with parameter $\lambda \cdot Area(\mathcal{D})$.

Table 2: Nearest neighbor ratio results for the deterministic and binomial expected distances

Analysis	Data	Deterministic ratio									Binomial ratio								
		Pipe	S1	S2	S3	S4	S5	S6	S7	S8	Pipe	S1	S2	S3	S4	S5	S6	S7	S8
Complete set	ILI1Int	0.28	0.6	0.23	0.13	0.27	0.31	0.21	0.59	0.21	0.17	0.24	0.17	0.05	0.16	0.22	0.12	0.28	0.14
	ILI2Int	0.61	0.78	0.44	0.49	0.55	0.47	0.6	0.65	0.35	0.45	0.47	0.37	0.40	0.42	0.39	0.45	0.37	0.26
	ILI1Ext	1.35	3.42	NR*	0.83	3.68	0.06	29.8	20.3	0.91	0.25	0.58	NR	0.07	0.29	0.00	1.47	10.4	0.16
	ILI2Ext	1.19	2.4	NR	1.7	6.64	0.18	0.03	0.3	1.57	0.28	0.50	NR	0.21	0.67	0.12	0.00	0.20	0.31
Segments-without 1m welds	ILI1Int	1.08	1.6	0.96	0.95	1	1.02	1.01	1.17	0.94	0.83	0.78	0.87	0.87	0.87	0.87	0.84	0.79	0.81
	ILI2Int	1.06	1.2	1.12	1.03	0.99	1.08	0.98	1.03	0.95	0.78	0.70	0.86	0.81	0.76	0.85	0.76	0.75	0.79
	ILI1Ext	0.95	1.33	NR	0.97	0.85	1.26	1.41	0.74	0.68	0.53	0.60	NR	0.86	0.59	0.66	0.93	0.55	0.42
	ILI2Ext	1.05	1.43	NR	1.01	1.25	1.26	0.58	0.83	0.58	0.55	0.61	NR	0.66	0.67	0.58	0.50	0.69	0.37
Welds up to 1m	ILI1Int	0.73	0.71	0.69	0.77	0.74	0.78	0.67	0.73	0.72	0.58	0.57	0.55	0.61	0.57	0.63	0.53	0.60	0.56
	ILI2Int	0.84	0.89	0.83	0.9	0.85	0.78	0.85	0.91	0.78	0.65	0.68	0.67	0.69	0.64	0.62	0.64	0.73	0.62
	ILI1Ext	0.64	0.68	NR	0.88	1.25	0.15	0.45	0.72	0.57	0.46	0.47	NR	0.53	0.75	0.12	0.35	0.61	0.40
	ILI2Ext	0.76	0.65	NR	0.87	0.77	1.32	0.39	0.81	0.76	0.56	0.46	NR	0.58	0.54	0.91	0.32	0.71	0.52

*NR: No defects reported
S1: Soil 1, S2: Soil 2, S3: Soil 3, S4: Soil 4, S5: Soil 5, S6: Soil 6, S7: Soil 7, S8: Near urban zone.

The results were determined for the entire pipeline and each type of soil, considering i) the complete set of reported defects, ii) the mean ratio per segment (between consecutive joint welds), but omitting 1m to the welds, and iii) the welds up to 1m for each side (Table 2). The results indicate that corrosion defects at the inner wall tend to be clustered for each type of soil and the entire pipeline if the complete set is used as the domain $\mathcal{D}$, while the outer wall tends to be dispersed, especially for the Soil 6 and Soil 7. However, if the domain is reduced to the segments between two consecutive weld joints, the deterministic ratio suggests that defects follow almost random dispersion in both pipe walls. This pattern is confirmed for the second and third soil for the simulation results. Finally, the results regarding the weld joints clearly show that defects tend to be clustered, as it was discussed before.

The results mentioned above suggest that defects do not follow a CSR distribution along the entire pipeline, and although defects may be located randomly between weld joints, this assumption could overestimate the potential condition near to the welding joints and the HAZ zone.

5 Concluding remarks & future work to locate new defects

The assumption of Complete Spatial Randomness (CSR), commonly implemented for the position of new corrosion defects in onshore pipelines, was evaluated using the nearest neighbor criterion based on two ILI measurements. This criterion suggests if the defects are distributed randomly, or if they tend to be clustered or dispersed. The results indicate that although defects may follow a CSR distribution between small segments (12 meters), the distribution along the pipeline depends on the type of soil and the distance to the welding joints. In the first place, inner corrosion tends to be clustered homogeneously along the pipeline, and external corrosion seems to be dispersed, especially, near to welding joints. In the second place, pitting corrosion tend to be near the fusion and the Heat Affected Area (near to 10cm of the welding joints), which was also pointed out by other researchers [10].

The location of new defects could be simulated using a Point Pattern Analysis following a non- homogeneous Poisson Process. This process would require to estimate the intensity $\tilde{\lambda}(x)$ upon to a given location x, which can be determined using a kernel smoothing estimator as follows:

$$\tilde{\lambda}(x) = \frac{1}{h^2} \sum_{i=1}^{n} \kappa \left(\frac{\|x - x_i\||}{h} \right) / q(\|x\|), \tag{1}$$

where $q(\|x\|)$ is a border correction, h is a bandwidth associated with the smoothness level, and $\kappa(\cdot)$ is a kernel function that is symmetric like the quartic or Gaussian kernels. The tunning of this intensity from the inspection data is contemplated as future work.

The reliability assessment of a corroding pipeline is a complex problem that should contemplate the generation of new defects. These defects must be located based on trained approaches that consider the current condition of the pipeline, and the point pattern analysis could be an interesting alternative for this purpose. For the reliability assessment this location can be used jointly with random size of the new defects (i.e., depth, length and width) based on the information reported by the ILI tool. In this regard, the probability density functions of the depth, length and width dimensions can be used for each type of defect, pipe wall, and inspection like the ones depicted in Figure 5 for defects with a defect depth lower than $0.15t$.

References

[1] H. Castaneda and O. Rosas, *External Corrosion of Pipelines in Soil*, ch. 20, pp. 265–274. John Wiley & Sons, Ltd, 2015.

[2] H. Wang, A. Yajima, R. Y. Liang*, and H. Castaneda, "Bayesian Modeling of External Corrosion in Underground Pipelines Based on the Integration of Markov Chain Monte Carlo Techniques and Clustered Inspection Data," *Computer-Aided Civil and Infrastructure Engineering*, vol. 30, no. 4, pp. 300–316, 2015.

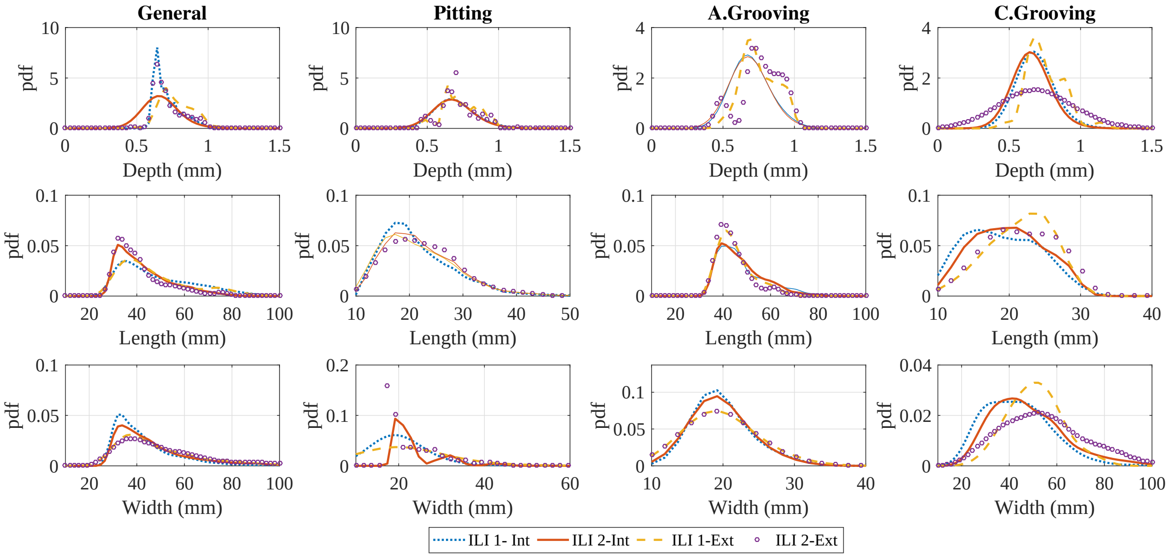

Figure 5: Depth, length, and width for the newly reported defects per category

[3] POF, "Specifications and requirements for intelligent pig inspection of pipelines," tech. rep., Pipeline Operators Forum, 2008.

[4] S. Zhang and W. Zhou, "Cost-based optimal maintenance decisions for corroding natural gas pipelines based on stochastic degradation models," *Engineering Structures*, vol. 74, pp. 74 – 85, 2014.

[5] S. Miran, Q. Huang, and H. Castaneda, "Time-Dependent Reliability Analysis of Corroded Buried Pipelines Considering External Defects," *Journal of Infrastructure Systems*, vol. 22, no. 3, p. 04016019, 2016.

[6] K. Dzioyev, K. Basiyev, G. Khabalov, and E. Dzarukayev, "Stress corrosion processes in the metal and welded joints in gas pipelines," *Welding International*, vol. 28, no. 9, pp. 717–721, 2014.

[7] P. Prevéy and D. Hornbach, *Residual Stress in Pipelines*. Wiley, 2015.

[8] D. Dorling and J. Gianetto, *Pipeline welding from the perspective of Safety and Integrity*. Wiley, 2015.

[9] J. Davis, *Corrosion of Weldments*. ASM International, 2006.

[10] I. Chaves and R. Melchers, "Pitting corrosion in pipeline steel weld zones," *Corrosion Science*, vol. 53, no. 12, pp. 4026 – 4032, 2011.

[11] Z. Śloderbach and J. Pająk, "Determination of ranges of components of heat affected zone including changes of structure," *Archives of Metallurgy and Materials*, vol. Vol. 60, no. 4, pp. 2607–2612, 2015.