UDC 51-74:53.083.8 DOI: 10.18698/1812-3368-2022-1-22-38

DEFINING A TIME-AVERAGE GROWTH RATE OF A CORROSION DEFECT FROM THE DATA OF ANY NUMBER OF INSPECTIONS

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Abstract

Although the corrosion rate varies with time depending on changing ambient conditions the time-average corrosion rate becomes stable 5 years later defect initiation. Therefore, a remaining useful life of a thin-walled structure is generally estimated using time-average growth rates of its revealed corrosion defects determined after periodic inspections according to data of inaccurate measurements of a remaining wall thickness. This paper presents a new approach to defining both initiation time of a corrosion defect and the time-average growth rate of the defect from the data of any number of inspections. A ratio of measured remaining to initial wall thickness is taken complying with a beta-distribution at a point of measurement, as it varies in finite interval [0; 1]. The parameters of the beta-distribution are obtained from analysis of measurement data and sizing uncertainties. Initiation time of the corrosion defect is determined with the method of maximum likelihood. The estimates of both mathematical expectation and variance of time-average growth rate of the corrosion defect are obtained using *k*-nearest neighbours (*k*NN) method from the data of all inspections. The presented approach is validated in a virtual experiment where both the true time of initiation, and the true time-average corrosion rate are specified

Keywords

Corrosion modelling, defect initiation, integrity prediction, machine learning, residual operating life, sizing uncertainty, thin-walled structure

Received 27.05.2021
Accepted 21.06.2021

Introduction. When residual lifetime of a structure is evaluated, underestimation of growth rates of corrosion defects can lead to structural failure while overestimation will cause undue frequent repairs [1–3]. Although it seems trivial, locating one and the same corrosion defect in subsequent inspections is an arduous problem, which, however, can be solved for in-line inspections (ILI) of pipelines on the basis of existing probabilistic models [4, 5].

The corrosion rate is estimated from the remaining wall thickness which is measured with poor accuracy at the time of inspections [2, 6–8]. Growth rates of corrosion defects are obtained with great errors [7, 9] and can possess even negative values [2, 10] that are never observed. Therefore, measurement errors of all inspections must be taken into account for estimation of the corrosion rate and the remaining time to failure with the better accuracy [2].

There are very few data sets published which can be used for validation of corrosion models [11]. The published empirical data show the non-linear dependence of the remaining wall thickness on time [11–13]. However, most published data about corrosion of thin-walled structures are from laboratory experiments rather than from field observations [14–20]. Although the laboratory experiments are important to gain deeper understanding of the corrosion phenomena, operational conditions of a thin-walled structure may differ markedly from experimental ones. Worst of all, the operating conditions may unpredictably vary affecting the corrosion rate of the structure in operation [21, 22]. It was also shown, that the time-average corrosion rate becomes stable 5 years later defect initiation [1]. Therefore, the time-average corrosion rate obtained from field observations is the most reliable parameter, both for prediction of technical condition of the thin-walled structure and for adjustment of corrosion models, developed in academic and research institutions to field conditions. Such adjustment has always been a challenging problem [23].

The poor accuracy of sizing of corrosion features coupled with random variation of corrosion rate in field conditions is the reason why the standard practice relies on time independent rate of growth of corrosion defect [8, 12, 21, 24–31].

The methods for estimating growth rates of corrosion defects can be based on deterministic or probabilistic models [8, 22, 32–34]. Purely deterministic models can be relatively reliable for high corrosion rate and accurate estimates of the depth of material loss obtained from special processing of measurement data [8]. However, the deterministic models require feature matching, do not allow taking into account measurement errors of all inspections and estimating the time-average growth rate of corrosion defect with tolerance probability of its underestimation [2, 32]. Probabilistic or stochastic models are generally based on Markov process, Gamma process or inverse Gaussian process [8, 33, 35]. Purely probabilistic or stochastic models require statistically homogenous data and may not be suitable for modelling single corrosion defects [2, 8, 32, 36].

Unlike earlier published method [3] aimed at modelling non-linear corrosion growth, the presented approach is based on application of *k*-nearest neighbours (*k*NN) method to determining a time-average growth rate of a corrosion defect from the data of any number of inspections. It allows estimating the time of the defect initiation with the method of maximum likelihood and is suitable for predictive modelling of steady rate corrosion at a point of measurement with specified tolerance probability of underestimation of corrosion rate.

Accepted assumptions, data and methods for solving the problem. The ratio of measured remaining wall thickness to initial wall thickness is taken complying with a beta-distribution at a point of measurement, because the beta-distribution:

1) has finite interval of change of random variate [0; 1];

2) allows assigning zero modal value to zero ratio of measured remaining wall thickness to initial wall thickness while taking nonzero mathematical expectation;

3) allows a unit modal value with mathematical expectation less than 1 when the wall material has not been detected;

4) approximates Gauss distribution at sufficiently great values of distribution parameters α and β.

Preparation of initial data. Initial data include the age of a structure, a warranty period of protective coating, total number of inspections I, when a defect of material loss was detected, measurement errors of flaw detectors used for the inspections and the number of measurements performed at each point during inspection, dates of the inspections and measurement data.

The age of the structure is determined by date of construction T_c according to certificate, or if it is unknown then by the date of putting into operation minus 1 year.

Each inspection is assigned number i, date of inspection T_i, estimate of measured wall thickness $\overline{t_i}$ near the defect and estimate of minimal remaining wall thickness $\overline{t_{r\,i}}$ at the location of the defect. The estimates of the wall thickness can be obtained according to R 50.2.038, GOST R 8.736 or JCGM 100, ISO/IEC Guide 98-4 from N_i measurements at each point by formulae

$$\begin{aligned} \overline{t_i} &= \sum_{j=1}^{N_i} t_{i\,j} \Big/ N_i; \\ \overline{t_{r\,i}} &= \sum_{j=1}^{N_i} t_{r\,i\,j} \Big/ N_i, \end{aligned} \qquad (1)$$

where $t_{r\,i\,j}$ is the minimal remaining wall thickness measured the j-th time during the i-th inspection at the location of the defect; $t_{i\,j}$ is the wall thickness measured the j-th time during the i-th inspection near the defect.

If the difference between the nominal wall thickness t and the value of $\overline{t_i}$ obtained from formula (1) exceeds sizing uncertainty, then the massive corrosion is observed and it is reasonable to take $\overline{t_i} = t$.

Calculating the parameters of the beta-distribution. The i-th inspection at each measurement point is assigned: estimate of relative remaining wall thickness

$$\gamma_i = \left(\overline{t}_{r\,i}/t\right)\left(t/\overline{t_i}\right),$$

and its variance D_i for single

$$D_i = S_{\Theta\,i}^2 \tag{2}$$

or multiple measurement of the wall thickness

$$D_i = S_{\Sigma\,i}^2. \tag{3}$$

In (2), (3) $S_{\Theta\,i}$ is a root mean square deviation, caused by residual bias during the i-th inspection, $S_{\Theta\,i} = \Theta_i\big/\sqrt{3}$; $S_{\Sigma\,i}$ is a total root mean square deviation of multiple measurement during the i-th inspection according to measurement standards GOST R 8.736 or JCGM 100,

$$S_{\Sigma i} = \sqrt{\Theta_i^2\big/3 + D_{\gamma i}\big/N_i},$$

where Θ_i is a residual bias of a flaw detector used for the i-th inspection, which is determined according to a performance specification of the detector by boundaries $\pm\Theta_i$ relative to the nominal wall thickness t for probability of detection P_d; $D_{\gamma i}$ is a variance of the relative remaining wall thickness at the location of the defect at the i-th inspection obtained from formula

$$D_{\gamma i} = D_{t_{r\,i}}\, D_{r\,i}\big/t^2 + \overline{t}_{r\,i}^{\,2}\, D_{t_{r\,i}}\big/t^4 + \overline{r_i}^{\,2} D_{r\,i},$$

where $D_{t_{r\,i}}$ is a variance of the measured remaining wall thickness at the location of the defect,

$$D_{t_{r\,i}} = k_N^2 \sum_{j=1}^{N_i}\left(t_{r\,ij} - \overline{t}_{r\,i}\right)^2\Big/\left(N_i - 1\right);$$

$D_{r\,i}$ is a variance of the ratio of the nominal wall thickness to the measured wall thickness near the defect,

$$D_{r\,i} = k_N^2\Big/\left(N_i - 1\right)\sum_{j=1}^{N_i}\left(t/t_{i\,j} - \overline{r_i}\right)^2,$$

$k_N = \sqrt{(N_i - 1)/2}\,\Gamma\left([N_i - 1]/2\right)\left[\Gamma\left(N_i/2\right)\right]^{-1}$ is an adjustment coefficient; $\overline{r_i}$ is an arithmetic mean ratio of the nominal wall thickness to the measured wall thickness near the defect,

$$\overline{r_i} = \left(1/N_i\right) \sum_{j=1}^{N_i} t/t_{ij}.$$

The beta-distribution of relative values of the measured remaining wall thickness has parameters α_i, β_i, modal value $\mathrm{Mo}_{\gamma i} = \left(\alpha_i - 1\right)/\left(\alpha_i + \beta_i - 2\right)$, and variance $D_i = \alpha_i\beta_i / \left[\left(\alpha_i + \beta_i\right)^2\left(\alpha_i + \beta_i + 1\right)\right]$. The relative remaining wall thickness obtained from measurements is assumed to be the most probable value $\mathrm{Mo}_{\gamma i} = \gamma_i$. Parameters α_i, β_i are determined for the i-th inspection from the system of equations

$$\begin{aligned} &\alpha_i^3 + a_2\alpha_i^2 + a_1\alpha_i + a_0 = 0; \\ &\beta_i = \left(\alpha_i - 1\right)/\mathrm{Mo}_{\gamma i} - \alpha_i + 2. \end{aligned} \tag{4}$$

Here

$$a_0 = 12\,\mathrm{Mo}_{\gamma i}^3 - 16\,\mathrm{Mo}_{\gamma i}^2 + 7\,\mathrm{Mo}_{\gamma i} - 1;$$

$$a_1 = \left[-2\,\mathrm{Mo}_{\gamma i}^3 + \left(16D_i + 1\right)\mathrm{Mo}_{\gamma i}^2 - 14D_i\,\mathrm{Mo}_{\gamma i} + 3D_i\right]/D_i;$$

$$a_2 = \left(\mathrm{Mo}_{\gamma i}^3 - \mathrm{Mo}_{\gamma i}^2 + 7D_i\,\mathrm{Mo}_{\gamma i} - 3D_i\right)/D_i.$$

If the measurement error is not greater than permissible by ISO/IEC Guide 98-4 or GOST 8.051 then equation (4) has always 3 different real roots, the first of which

$$\alpha_{i1} = 2\sqrt{-p/3}\cos\left(\psi/3\right) - a_2/3$$

is chosen to ensure the better approximation of Gauss distribution with the beta-distribution. Here $p = -a_2^2/3 + a_1$, and ψ is the root of equation $\cos\psi = \left(-q/2\right)\sqrt{\left(-p/3\right)^{-3}}$ in which $q = 2a_2^3/27 - a_2 a_1/3 + a_0$.

The mathematical expectation of the beta-distribution of the relative remaining wall thickness at the i-th inspection has expression $M_{\gamma i} = \alpha_i/\left(\alpha_i + \beta_i\right)$.

Results. A time-average rate of material loss can be estimated if both time of a defect initiation and remaining wall thicknesses measured during inspections are known.

Time of a defect initiation. If only one inspection was carried out during operation time and the corrosion defect was revealed, then estimated time T_0

of defect initiation is often supposed to be equal to the date of bringing into service [12], the date of construction [32] or the date of construction incremented by the warranty period of the protective coating. However, such approach does not imply probability-based estimate and may result in underestimation of the time-average corrosion rate. A more valid estimate would be based on *g*-percentile lifetime of the protective coating. If it is unknown, then the mathematical expectation of time T_0 is reasonable to take halfway between the end of the warranty and the time of the first inspection which are the bounds of the time interval for Type B evaluation of standard uncertainty according to R 50.2.038 or JCGM 100.

If two inspections were carried out and the defect of material loss was found during both inspections, then estimated time of defect initiation T_0 is found from equation

$$\left(T_1 - T_0\right) \big/ \left(T_2 - T_0\right) = \left(1 - M_{\gamma 1}\right) \big/ \left(1 - M_{\gamma 2}\right), \tag{5}$$

where T_1, T_2 are dates of the first and the second inspections respectively, for which $M_{\gamma 1}$ and $M_{\gamma 2}$ are respective mathematical expectations of relative values of the measured remaining wall thickness.

If the solution of equation (5) shows that the defect is older than the structure, or was initiated after revealing, then T_0 is taken equal to the date of the latest inspection, when the defect had not been revealed. If the defect was detected during the first of two inspections, then the defect is assumed to be initiated halfway between the end of the warranty period of the protective coating and the time of the first inspection.

If the defect was detected during three or more inspections, then time T_0 of defect initiation and the preliminary estimate of time T_d of occurrence of a through hole can be obtained by the method of maximum likelihood from system of equations

$$\begin{aligned} & T_0 \sum_{i=1}^{I} \left(\alpha_i - 1\right) \big/ \left(T_d - T_i\right) + T_d \sum_{i=1}^{I} \left(\beta_i - 1\right) \big/ \left(T_d - T_i\right) = \\ & \qquad = \sum_{i=1}^{I} T_i \left(\alpha_i + \beta_i - 2\right) \big/ \left(T_d - T_i\right); \\ & T_0 \sum_{i=1}^{I} \left(\alpha_i - 1\right) \big/ \left(T_i - T_0\right) + T_d \sum_{i=1}^{I} \left(\beta_i - 1\right) \big/ \left(T_i - T_0\right) = \\ & \qquad = \sum_{i=1}^{I} T_i \left(\alpha_i + \beta_i - 2\right) \big/ \left(T_i - T_0\right); \end{aligned} \tag{6}$$

Owing to measurement errors, the estimate from system of equations (6) may show that the defect was initiated before construction or after inspection when it had been already revealed. To correct such errors the remaining wall thickness measured during the last inspection would be decreased by the confidence bound of the measurement error.

If by preliminary estimate from system of equations (6) the through hole had appeared in the wall before the inspection, when no hole was detected, then the remaining wall thickness measured during the first inspection would be decreased by the confidence bound of the measurement error.

Time-average growth rate of a defect. Since relative measured values of the remaining wall thickness are nearly symmetric [37], the beta-distribution approximates to Gauss distribution [38] which can be taken as distribution of estimated values of time-average growth rate of the defect of material loss.

Variance D_{Vi} and confidence bounds ΔV_i of estimation error of the time-average growth rate of the defect detected with probability P_d during the i-th inspection have expressions for single measurements

$$\begin{gathered}\Delta V_i = k_d \sqrt{3 D_{Vi}};\\ D_{Vi} = D_i \left[\overline{t}_i / \left(T_i - T_0 \right) \right]^2\end{gathered} \qquad (7)$$

or for multiple measurements

$$\begin{gathered}\Delta V_i = k_{\Sigma i} \sqrt{D_{Vi}};\\ D_{Vi} = D_i \left[\overline{t}_i / \left(T_i - T_0 \right) \right]^2 .\end{gathered} \qquad (8)$$

In (7), (8), k_d is an adjustment coefficient for confidence bounds of a measurement error obtained from equation for probability of the defect detection,

$$1 \Big/ \sqrt{2\pi} \int\limits_{-k_d}^{k_d} \exp\left(-u^2/2 \right) du = P_d;$$

$$k_{\Sigma i} = \left(t_d \sqrt{D_{\gamma i} / N_i} + \Theta_i \right) \left(\sqrt{D_{\gamma i} / N_i} + \Theta_i \Big/ \sqrt{3} \right)^{-1}$$

is a coefficient dependent on ratio of a random error to a residual bias in which t_d is the P_d-th quantile of Student's distribution (GOST R 8.736; JCGM 100).

Time-average growth rate V_i of the defect is preliminary estimated for inspection i using formula

$$V_i = \left(1 - M_{\gamma i} \right) \overline{t}_i / \left(T_i - T_0 \right) + \Delta V_i .$$

The expected value of the time-average growth rate of corrosion defect is obtained using *k*NN as weight-average growth rate

$$V_W = \sum_{i=1}^{I} W_i V$$

with confidence bounds of estimation error

$$\Delta V_W = \sum_{i=1}^{I} W_i \Delta V_i$$

and weight-average variance

$$D_W = \sum_{i=1}^{I} W_i^2 D_{Vi}.$$

Weight coefficients W_i for the estimation are determined from expression

$$W_i = \left(D_{Vi} \sum_{j=1}^{I} 1 \big/ D_{Vj} \right)^{-1}.$$

Weight coefficient W_i corresponds with the accuracy of the preliminary estimate of time-average growth rate of the defect at the i-th inspection.

The estimate of time-average growth rate V_d of the defect can be obtained for probability of underestimation Q_V using truncated Gauss distribution:

$$Q_V = 1 - \int_0^{V_d} \exp\left[-(v - V_w)^2 \big/ (2D_w) \right] dv \big/ \sqrt{2\pi D_w} \times$$
$$\times \left(1 - \int_{-\infty}^{0} \exp\left[-(v - V_w)^2 \big/ (2D_w) \right] dv \big/ \sqrt{2\pi D_w} \right)^{-1}.$$

Time of occurrence of a through hole. Time of occurrence of the through hole can be estimated from expression

$$T_{Q_V} = T_0 + t \big/ V_d$$

with probability of overestimation Q_V by the results of all inspections when the defect was detected, and its lower ΔT_{1Q_V} and upper ΔT_{2Q_V} confidence bounds are obtained from expressions for single measurements:

$$\Delta T_{1Q_V} = T_0 + t \left(1 - \sqrt{3} \sum_{i=1}^{I} k_i W_i S_{\Theta i} \right) \Big/ \left(V_d + \Delta V_W \right); \qquad (9)$$

$$\Delta T_{2Q_V} = T_0 + t\left(1+\sqrt{3}\sum_{i=1}^{I} k_i W_i S_{\Theta i}\right)\Big/\left(V_d - \Delta V_W\right) \qquad (10)$$

or from expressions for multiple measurements

$$\Delta T_{1Q_V} = T_0 + t\left(1-\sum_{i=1}^{I} k_{\Sigma i} W_i S_{\Sigma i}\right)\Big/\left(V_d + \Delta V_W\right);$$

$$\Delta T_{2Q_V} = T_0 + t\left(1+\sum_{i=1}^{I} k_{\Sigma i} W_i S_{\Sigma i}\right)\Big/\left(V_d - \Delta V_W\right).$$

In (9), (10), k_i is an adjustment coefficient defined for taken confidence probability P_d and the number of components of each $S_{\Theta i}$ according to measurement standard (R 50.2.038; JCGM 100).

Computational experiment. *Problem formulation.* By the data of simulated ILI determine the year of initiation of a corrosion defect and the year of occurrence of a through hole in a wall of a trunk pipeline, which was put into operation on 01 February 1963. The nominal wall thickness of the pipe is t = 11.9 mm. The warranty period of the protective coating is 7 years.

Deviation of the remaining wall thickness measured during ILI includes both bias and random scattering error [37, 39]. Deviations of measurement data from true values were simulated using generator of normally distributed random numbers for the probability of detection of the defect equal to P_d = 0.9. The bias is presented with uncertainty Type B. The confidence bound of the residual bias was taken equal to 0.5 mm in inspections performed on 02 June 1993, 18 July 1998, 08 June 2008, and $0.15\,t$ in inspections performed on 06 July 2003, 25 August 2013, 19 July 2018.

The taken true time of initiation of a corrosion defect is 01 January 1987. The taken true time-average growth rate of the defect is V_t = 0.15 mm/year until occurrence of a through hole in 2066.

The remaining wall thickness by the data of single measurements at the point. The results of simulated in-line inspections of the trunk pipeline are presented in Fig. 1. The probability of underestimation of time-average growth rate V_d of the defect is equal to $Q_V = 10^{-6}$ in all diagrams in Fig. 1.

The estimate of time-average growth rate V_d of the defect according to the data of the first inspection is 0.431 mm/year for the year 1985 taken for the time of defect initiation that allows predicting occurrence of the through hole in 2012 (Fig. 1, *a*). If the data of both the first and the second inspections are considered, then the estimate of V_d becomes 0.257 mm/year, the estimated year of defect initiation changes to 1982 (Fig. 1, *b*), and the through hole would be expected in 2029. The data of the first three inspections give 1980 as the year of the defect

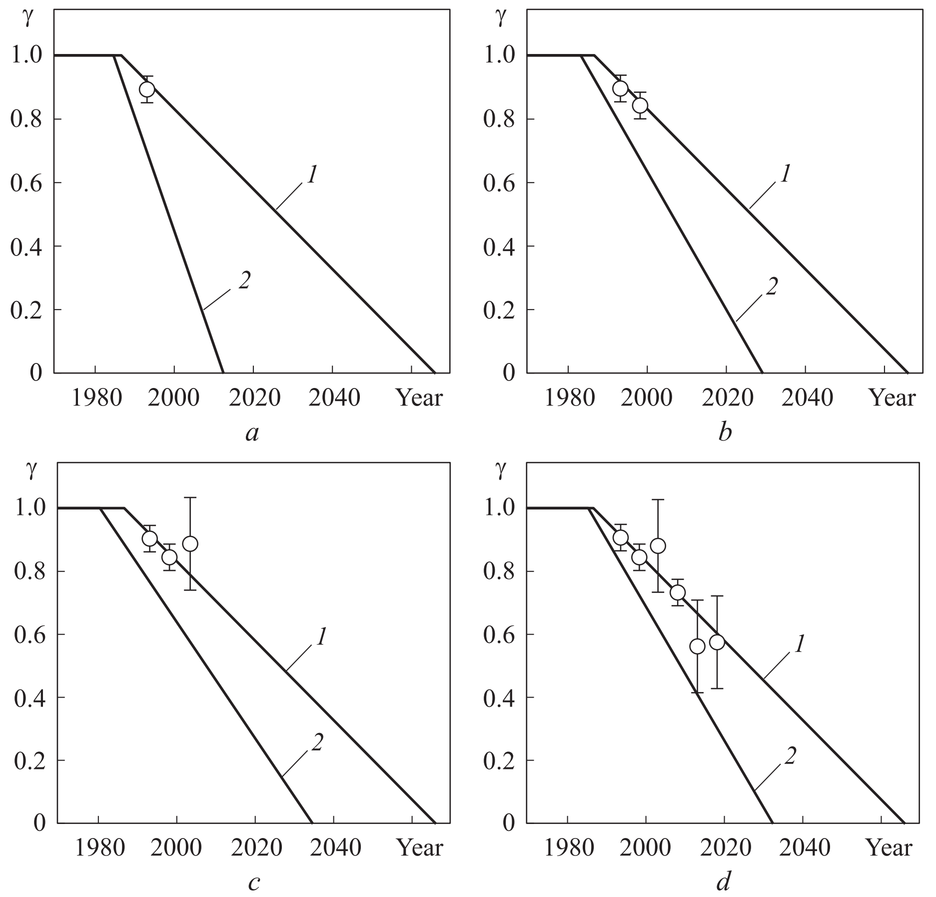

Fig. 1. The relative remaining wall thickness from the data of single measurements: *1*) true value; *2*) estimated value

initiation, V_d = 0.216 mm/year, and year 2035, when the through hole would be expected (Fig. 1, *c*). The data of all six inspections lead to the conclusion that the defect appeared in 1985, V_d = 0.253 mm/year, which would cause occurrence of the through hole in the course of the year 2032 (see Fig. 1, *d*).

If the probability of V_d underestimation is changed from 10^{-6} (Fig. 2, *a*) to 10^{-3} (Fig. 2, *b*), then the estimates of time when the through hole would appear from the data of inspections verge towards the true value upward, although the confidence bounds of the estimates expand.

The remaining wall thickness by the data of multiple measurements at the point. Figures 3 and 4 show the results of simulated inspections of the thin-walled structure where the remaining wall thickness was measured four times at each point of measurement during each inspection. The probability of underestimation of time-average growth rate V_d of the defect is 10^{-6} for all diagrams in Fig. 3.

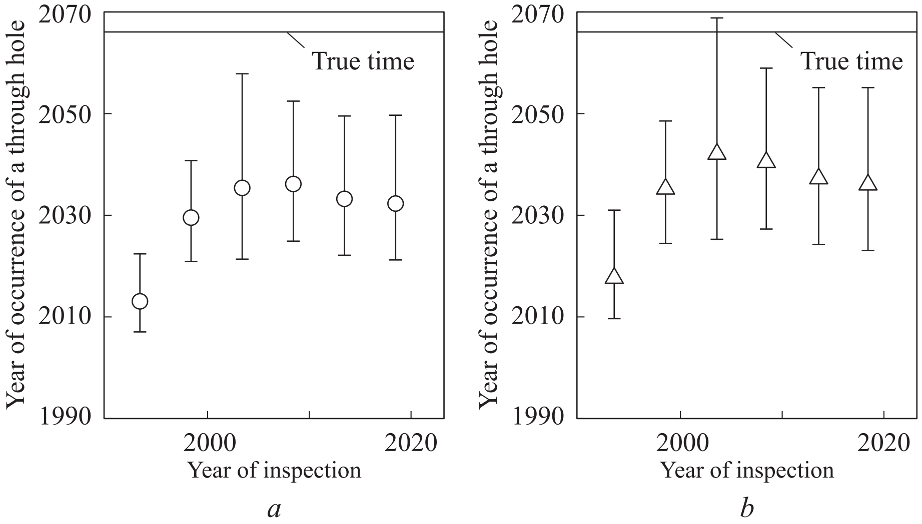

Fig. 2. Occurrence of a through hole from the data of single measurements

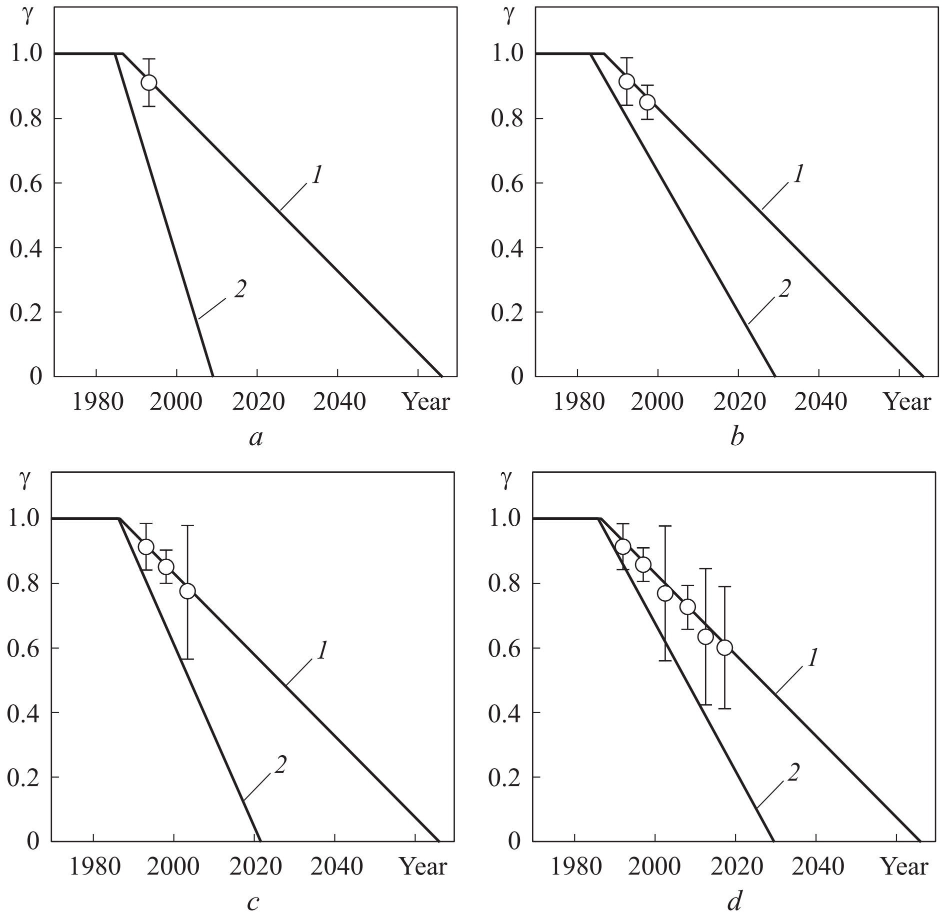

Fig. 3. The relative remaining wall thickness from the data of multiple measurements: *1*) true value; *2*) estimated value

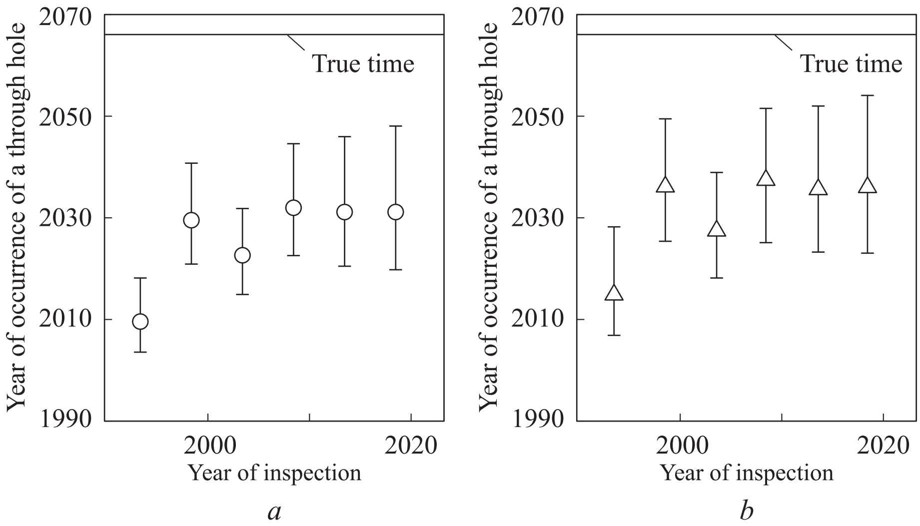

Fig. 4. Occurrence of a through hole from the data of multiple measurements

The data of the first inspection allow estimating time-average growth rate V_d of the defect as equal to 0.493 mm/year and predicting the occurrence of the through hole in 2009 as year 1985 is taken for the time of defect initiation (Fig. 3, *a*). If the data of the first two inspections are considered then the estimate of V_d becomes 0.264 mm/year, the time estimate of defect initiation changes to 1983 (Fig. 3, *b*), and the through hole would be expected in 2029. The data of the first three inspections suggest that the defect appeared in 1986, $V_d =$ $= 0.337$ mm/year, and the through hole would be expected in 2022 (Fig. 3, *c*). The data of all six inspections lead to the conclusion that the defect initiated in 1986, $V_d = 0.270$ mm/year, and the through hole would appear in 2031 (Fig. 3, *d*).

If the probability of V_d underestimation is changed from 10^{-6} (Fig. 4, *a*) to 10^{-3} (Fig. 4, *b*) the estimates of time when the through hole would appear from the data of inspections tend to the true value upward similarly to estimates obtained from the data of single measurements.

Discussion. *Features of the proposed method for estimating both time-average growth rate and initiation time of a corrosion defect.* The diagrams in Fig. 1 and Fig. 3 show that the confidence bounds for the estimated relative remaining wall thickness are wider for the case of multiple measurements, because both Type B evaluation of standard uncertainty and standard deviation of several measured values are taken into account. However, the mathematical expectations of relative remaining wall thickness estimated during different inspections are closer to the true values in all numerical experiments with simulation of multiple measurements. This causes the narrower confidence bounds for the estimated time of occurrence of the through hole in the case of multiple measurements performed at inspections (see Figs. 2, 4).

Applicability of the method for estimating time-average growth rate of a corrosion defect. During ILI, the remaining wall thickness is measured at points of a reference surface of the pipeline. Axis and angular coordinates of measurement points are determined with a known accuracy referring to the welded joints of pipes. Therefore, the measurement data collected using different flaw detectors in different inspections can be mapped and matched automatically [4–6]. Comparison of the data from different ILI allows estimating change of the remaining wall thickness of the pipe and growth of a corrosion defect at a point of measurement.

Time-average growth rate of a corrosion defect is the most reliable parameter for predictive modelling of corrosion, as such rate is robust both to measurement uncertainties caused by large errors in determining both coordinates of measurement points and the remaining wall thickness at these points during ILI and to uncertainties in parameters affecting the corrosion, as the corrosion rate itself actually changes with time in a random manner due to changing ambient conditions even for the same medium.

The proposed method can be used in combination with statistical approaches to reliability and risk analysis of hazardous industrial facilities [40–44].

Conclusion. The proposed method allows estimating both time-average growth rate of a corrosion defect and time of occurrence of a through hole in a thin wall from the data of any number of inspections perfomed with different measuring devices.

An increase in the number of inspections improves repeatability of estimates of both the time of the defect initiation and time of occurrence of a through hole in the wall within the confidence bounds of estimation errors.

Although the proposed method excludes negative estimates of corrosion rate and makes estimates of time-average corrosion rate less sensitive to measurement errors, the accuracy of such estimates highly depends on residual bias of a flaw detector used for the first inspection.

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Please cite this article as:

Galakhar A.S. Defining a time-average growth rate of a corrosion defect from the data of any number of inspections. *Herald of the Bauman Moscow State Technical University, Series Natural Sciences*, 2022, no. 1 (100), pp. 22–38.
DOI: https://doi.org/10.18698/1812-3368-2022-1-22-38